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Article

The Permian-Triassic Riftogen Rocks in the Norilsk Area (NW Siberian Province): Geochemistry and Their Possible Link with PGE-Cu-Ni Mineralization

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Abstract: The volcanic rocks in the Vologochan syncline, the Khikey River valley, and Mount Sunduk, within the Norilsk area in the NW Siberian large igneous province, have been studied. They belong to the Ivakinsky, Syverminsky, Gudchikhinsky, Khakanchansky, Nadezhdinsky, Tuklonsky, and Morongovsky Formations. These Formations consist of trachybasalts, picritic basalts and tholeiitic basalts with aphyric and porphyritic textures, and intersertal and poikiloofitic structures. For the first time, we demonstrate the variations in the structure and composition of these Formations along the strike, based on 151 analyses of the major and trace elements in the rocks. The thickness of all the Formations, excepting the Morongovsky, reduce dramatically from the Yenisey–Khatanga trough to the Tunguska syneclise, and they pinch out in the east of the Norilsk area and are attributed to riftogen (rift) basalts. The rock compositions also change in this direction, especially in the Gudchikhinsky and Nadezhdinsky Formations. The two subformations of the Gudchikhinsky formation, the lower and upper, disappear in the east, so the Gudchikhinsky consists only of high-Mg rocks, picritic basalts, and picrites. The composition of the Nadezhdinsky formation varies intensely in its (Gd/Yb)n and (Th/Nb) ratios from the Vologochan syncline to the Khikey River valley. These structural and compositional variabilities differ between the rift formations and the platform ones. Two gabbro–dolerite sills from these areas that are close to the Norilsk and Ergalakh intrusive complexes have been studied. The metal contents in volcanic and intrusive rocks are similar and do not differ from the barren rocks of the South Pyasinsky massif comprising the PGE-Cu-Ni deposits. Only the Gudchikhinsky Formation contains elevated Cu and Ni concentrations. These features and the coinciding spatial distribution of the ore-bearing intrusions and picrites of the Gudchikhinsky rocks in the Norilsk–Igarka paleorift suggest their genetic link. It is proposed that the initial sulfides could have been formed in the mantle, as the Gudchikhinsky picrites, transported to the lower crust, and then involved by the trap magmas in the origin of the ore-bodies in the Norilsk deposits.

Keywords: Siberian traps; rift and platform magmatism; Norilsk area; PGE-Cu-Ni deposit; geochemistry; REE

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1. Introduction

The origin of the extra-large PGE-Cu-Ni Norilsk deposits has been under discussion for several decades [1–10], etc. Many models have been suggested to explain the sulfide orebodies formation [11–16], but, as a rule, they regard the deposits' genesis as outside their tectonic setting. However, this is an example of the world-class deposits occurring within the large igneous provinces (LIPs) on Earth, e.g., in the Siberian large igneous province (SLIP, 250 Ma) [17–19]), contrary to other large Cu-Ni and PGE deposits [20–22]. This geological location of rich sulfide ores poses a question about the crucial role of magmatism in their genesis. We have shown previously that the deposits are not regularly distributed in the province; they occur only within narrow paleorift zones in the northern SLIP [23,24]. These zones include the Yenisey-Khatanga trough, Norilsk-Igarka paleorift, etc. They differ from other areas of the province by a diverse magmatism, varying from a mantle to a crustal origin. Thus, a magmatic PT evolution is critical for our understanding of the deposits' genesis. It can be reconstructed on the basis of the geochemical variations of the igneous rocks within the province, especially in the Norilsk area, which comprises the PGE-Cu-Ni deposits and a thick pile of volcanic rocks (3.5 km) [25,26].

Despite the long study of the volcanic rocks, their origin is still under discussion up to the present time. Initially, all magmatic rocks were considered as products of the fractional crystallization of a single magma [27]. Later, an idea about how many magmatic sources of basalts and intrusions appeared [28], where the magma mixed and its contamination by crustal material occurred. Later, the OIB, transitional, and WPB rocks in the Norilsk area were distinguished on the basis of a modern geochemical study [29–31]. Al'mukhamedov et al. [32] recognized two rock types, the rift and platform basalts. This division is consistent with the regional geology and rock geochemistry. However, all these constructions are based on single sections. For the first time, in this article, we present new data on the volcanic rocks, mainly from the lower part of the volcanic sequence in the Norilsk area (in the border of the Khantajsko-Rybninsky swell, Figure 1), that demonstrate their essential structural and geochemical variability in the space and their potential role in mineralization. These features differentiate these basalts from the overlapping typical traps that we characterized earlier [33].

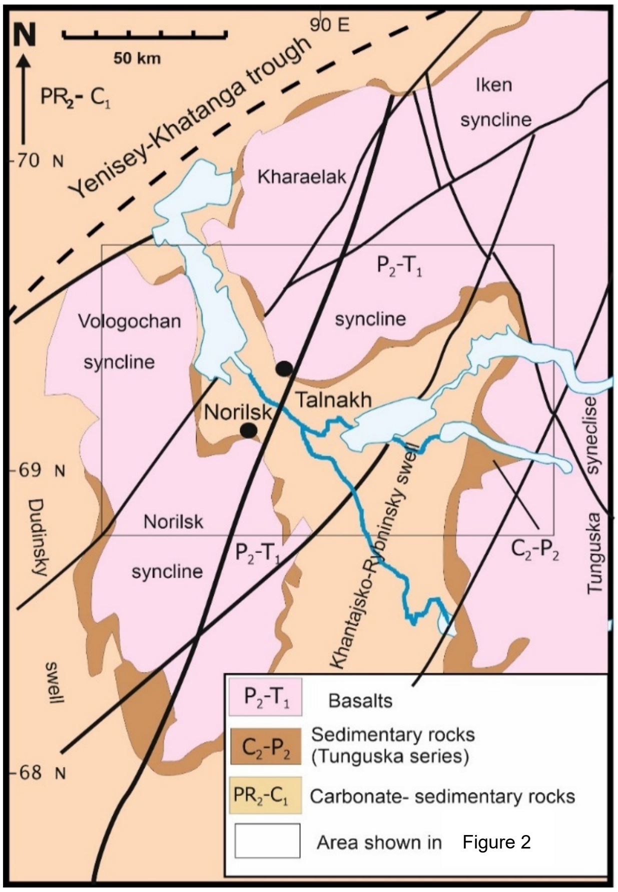

Figure 1. Schematic geological map of the Norilsk area.

2. Brief Information about the Geology of the Area

The Norilsk region is located in the northwestern part of the Siberian platform in the crustal block of elevated thickness [2,26,34]. Cambrian-Devonian carbonate-terrigenous rocks, coal-bearing terrigenous rocks of the Tunguska series (C_2-P_2), and volcanic rocks (P_3-T_1) are exposed on the surface of the area. The first two types form the modern surface of the Khantajsko–Rybninsky and Dudinsky swells, while the latter is widespread in the Norilsk–Kharaelakh trough and the western part of the Tunguska syneclise. The Norilsk-Kharaelakh trough consists of (from north to south) the following synclines: the Iken, Kharaelakh, Vologachan, and Norilsk (Figure 1). The volcanic rocks of the Norilsk area have been subdivided, on the basis of their petrographic features and chemical composition during the geological mapping [35], into eleven formations (from bottom to top): the Ivakinsky, Syverminsky, Gudchikhinsky, Hakanchansky, Tuklonsky, Nadezhdinsky, Morongovsky, Mokulaevsky, Kharaelakhsky, Kumginsky, and Samoedsky Formations. Some of the Formations are further subdivided into subformations. The lower Formations, including the Nadezhdinsky, are distributed only in the northeastern part of the Siberian platform, pinching out to the Tunguska syncline, while the upper Formations (starting with the Morongovsky) cover the whole Siberian platform. The Tuklonsky Formation occupies a restricted area in the northwestern Tunguska syneclise and disappears towards the Yenisey-Khatanga trough.

The intrusive rocks of the area are subdivided into several intrusive complexes [2,35], i.e., the Yergalakhsky subalkaline complex and the Norilsk, Ogonersky, Morongovsky, and Daldykansky, of a normal alkalinity. The intrusions are predominantly sill-shaped bodies, or, less frequently, dikes, and irregularly shaped massifs. The differentiated ultrabasic–basic mineralized intrusions belong to the Norilsk intrusive complex. Three of them, the Talnakh, Kharaelakh, and Norilsk 1, comprise world-class PGE-Cu-Ni deposits in the Kharaelakh and Norilsk synclines (Figure 1). The intrusions are ribbon-like bodies up to 12 km long and 2–4 km wide, and 100–300 m thick. Many publications describe their internal structure, mineralogy, and geochemistry [1–11,26,34], etc.

3. Objects and Methods

We have studied the volcanic sequences and intrusive rocks around the Khantajsko-Rybninsky swell, i.e., in the Vologochan syncline (borehole OB-36), in the Khikey River valley, and on Mount Sunduk (natural outcrops). Although the rocks in the last section were studied by Lightfoot et al. in 1994 [36], we used our results for these rocks obtained by the same methods as those applied for the first two sections. This approach gets better results from the rocks' comparison. The gabbro–dolerite sills were studied among the effusive rocks in the borehole OB-36, and in the Khikey River valley, and correlated with those previously characterized the South Pyasinsky and Vologochansky ore-bearing intrusions [37].

The samples for the analytical studies have been taken from the central parts of the basalt flows that are the least susceptible to secondary alterations. The determination of the major and trace elements was carried out in glasses on samples from the crushed rocks, ground to 200 mesh samples and fused in a high-voltage arc by an electron microprobe analysis (EPMA, using Jeol JXA 8200) and inductively coupled plasma mass spectrometry with a laser probe (LA-ICP-MS, ThermoFinnigan ELEMENT2), respectively, at the Max-Planck Institute for Chemistry, Mainz, Germany (analysts D. V. Kuzmin, B. Stoll, N. A. Krivolutskaya). These methods were described earlier [9,38]. The analyses of the minerals were carried out at the Vernadsky Institute of Geochemistry and Analytical Chemistry RAS, Moscow, using a Microzonde Cameca SX 100 (analyst N.N. Kononkova).

4. Results

There are four rock groups that could be distinguished in a field, regardless of their formation affiliation, which depends on the chemical composition of the rocks. The first one (the Ivakinsky Formation) represents dark-grey, almost black, fine-grained porphyritic rocks. They often contain coal and bitumen inclusions. The second group comprises greenish-grey tholeiitic basalts of the Syverminsky, Tuklonsky and Nadezhdinsky Formations. The third group combines large-grained black picrites and picritic basalts belonging to the Gudchikhinsky, Tuklonsky, and Nadezhdinsky Formations. The fourth and largest group consists of aphyric and porphyric grey basalts of the Nadezhdinsky and Morongovsky Formations.

Three main minerals (vol.%) form all the rock varieties, i.e., plagioclase (40–60), clinopyroxene (30–60), and olivine (0–40); orthopyroxene and the Fe-Ti oxides are the subordinate minerals (1–3 vol.%).

Very similar textures and structures are typical of the rocks of the different formations (Table 1, Supplementary Material Figures S1). The ophitic texture is the most widespread in the rocks, of which the chief characteristic is the idiomorphism of the palgioclase. It is characterized by aphyric basalts and the groundmass of the porphyritic rocks. Many flows have a poikilophitic texture, i.e., pyroxene completely encloses plagioclase laths. It is typical of the Syverminsky, Gudchikhinsky, Nadezhdinsky, and, especially, the Tuklonsky rocks. The texture and structure of the rock could change in one flow from contact with its inner part and, rarely, along the strike.

Table 1. Textural–structural characteristics of the effusive rocks, NW Siberian Platform.

Formation	Rock	Structure	Texture
Morongovsky	Tholeiitic basalt	Aphyric, porphyritic	Ophitic,
Nadezhdinsky	Tholeiitic basalt, Picritic basalt, Olivine basalt	Porphyritic, Glomeroporphyritic	Tholeiitic, ophitic, poikiloophitic
Tuklonsky	Tholeiitic basalt, Picritic basalt, Picrite	Aphyric porphyritic	Tholeiitic, Poikiloophitic
Khakanchansky	Tuff	Vitrophyric	
Gudchikhinsky	Picrite, picritic basalt, Olivine basalt	Porphyritic	Poikiloophitic
Syverminsky	Tholeiitic basalt	Aphyric	Tholeiitic, Poikiloophitic
Ivakinsky	Trachybasalt, Basaltic andesite	Porphyritic	Ophitic

The composition of rock-forming minerals depends on the composition of the parental magma; therefore, the most magnesium Fe-Mg rock-forming minerals and Ca-rich plagioclase are found in high-Mg rocks (MgO = 12–22 wt.%, Tables S2–S4), i.e., in olivine and picritic basalts, and picrites. For example, the Fo in olivine phenocrysts reaches 83 mol.%. in picrites of the Gudchikhinsky Formation and 75–76 in the Tuklonsky and Nadezhdinsky Formations (Supplementary Material Table S1 No 85, and 68, 17, respectively), while olivine in the groundmass of the Mokulaevsky basalts is enriched in Fe ($Fo_{45–47}$) (Table S1, No 1–3). The Mg# of clinopyroxene in the high-Mg rocks usually exceeds 80, and it is around 70 in the basalts. The basaltic andesites and trachybasalts have the lowest values Mg# (61–99, Table S1, No 104–106, 110–112). The composition of the plagioclase usually changes significantly in one sample (for example, Table S1, No 91–100). The tholeiitic basalts containing 6–8 wt.% MgO have a similar mineral composition [33].

4.1. Volcanic Sequence in the Vologochan Syncline

The lower seven formations from the distinguished ones in the Norilsk area participate in the structure of the Vologochan syncline, but they are unevenly distributed within it (Figures 2 and 3). A detailed study of the volcanic rocks in the borehole OB-36 shows the occurrence of only five formations in the section (Figure 4 and Supplementary Material Figure S1, Table 2). The rock attribution was realized on the basis of its texture and structure [35], and then was confirmed by the geochemical data. The individual basalt flows are isolated in the borehole, or the outcrops, according to the amygdale zones.

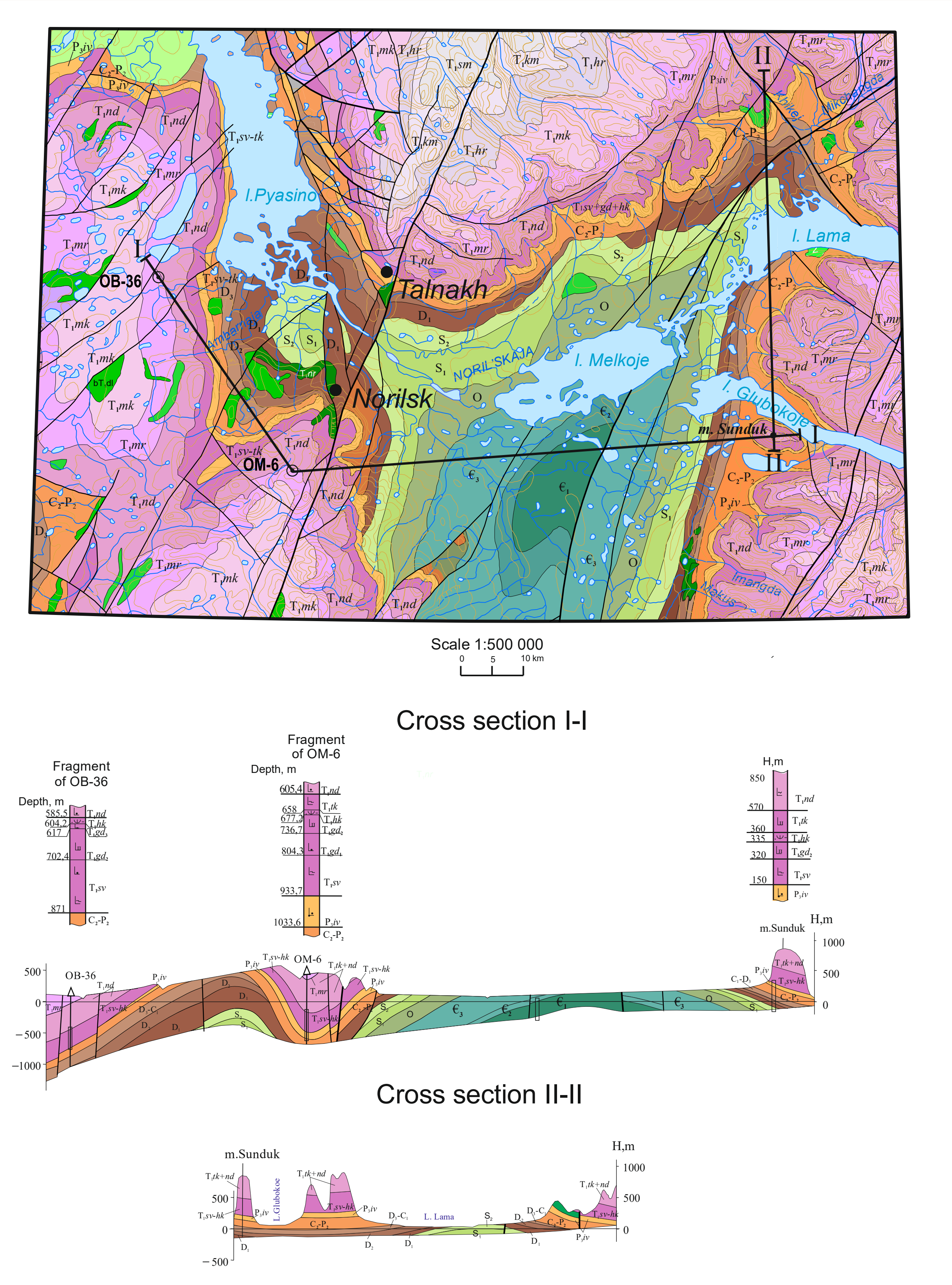

Figure 2. *Cont.*

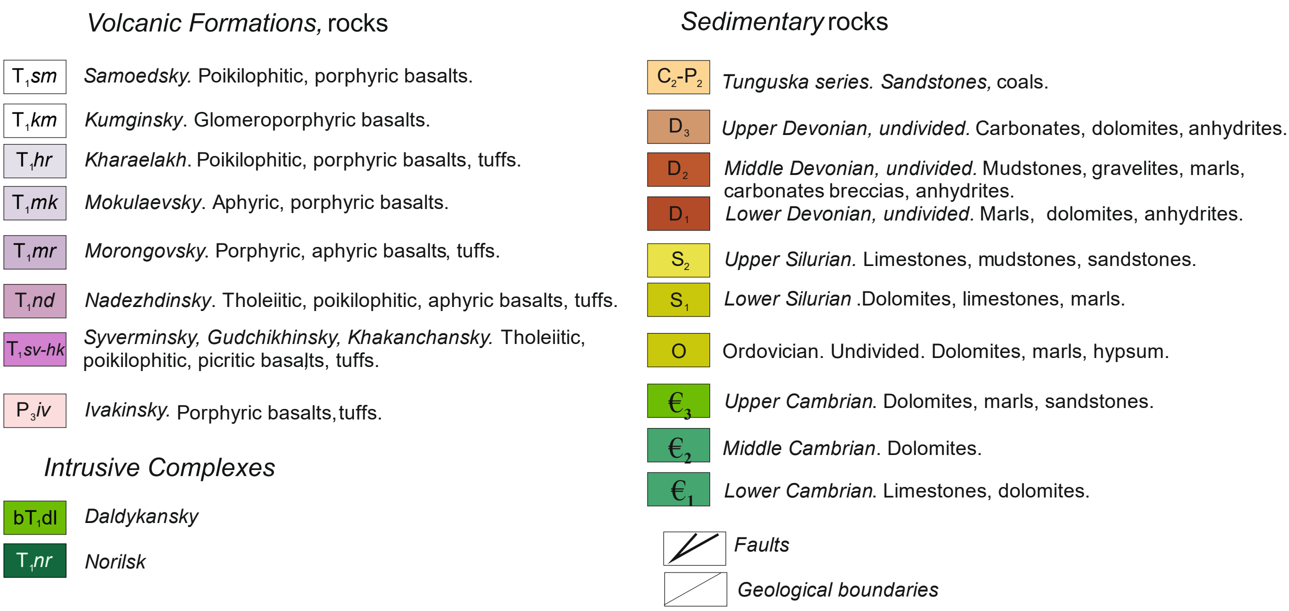

Figure 2. Geological map and cross-sections of the studied area.

The thickness of the tuff-lava sequence in the borehole OB-36 is 820 m. It should be noted that the lowest, the Ivakinsky Formation, which occurs in the neighboring sections, is absent in this borehole. The absence of the Ivakinsky Formation indicates that the first magma portions flowed onto a dissected surface, formed mainly by the terrigenous sediments of the Tunguska Series (Figure 3). The borehole OB-36 is located on the top hill in the Permian Period.

The Syverminsky Formation (T_1sv) covers the terrigenous sediments of the Tunguska Series. It consists of thin flows (3–5 m) in the lower part of the section and thick flows (up to 20 m) in its upper part. The greenish-grey color is typical of the rocks, due to the secondary minerals of the chlorite group that altered glass. The rocks have a middle-grained massive texture and a tholeiitic structure [34], and the flows contain thick amygdale zones (up to 80% of the flow volume). The Syverminsky Formation consists of 21 basalt flows in this area. The upper part of the section comprises poikilophitic basalts, while the lower one includes tholeiitic basalts. Two thin (1.5 and 2 m) tuff horizons have been identified between the basalt flows. The total thickness of the formation is 160 m.

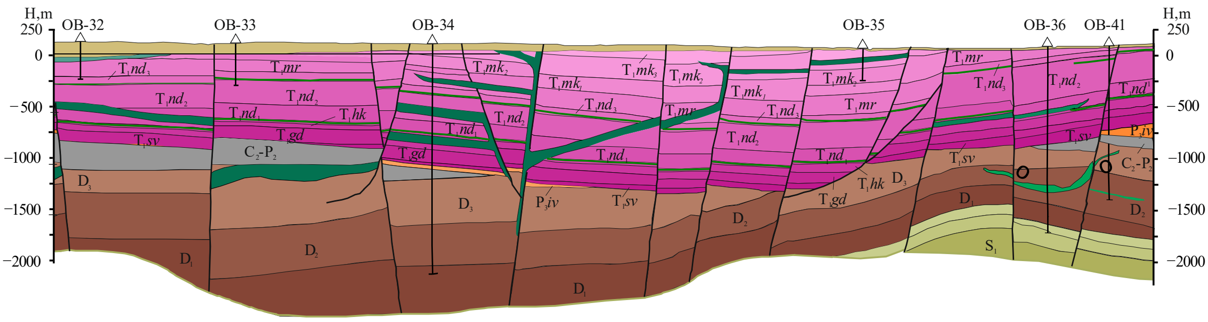

Figure 3. Cross-section the Vologochan syncline. Captions in Figure 2.

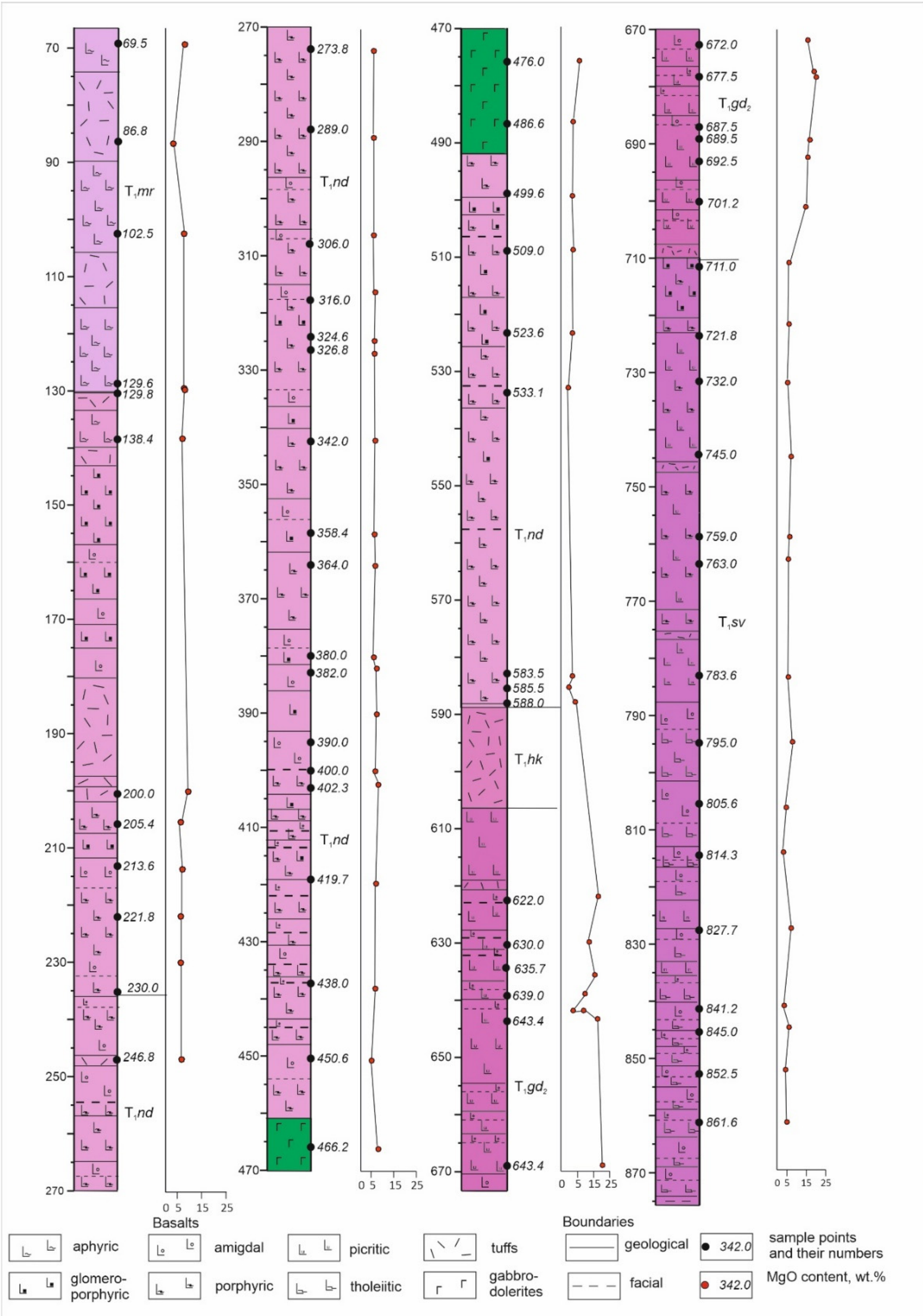

Figure 4. Volcanic section in the Vologochan syncline and MgO distribution in borehole OB-36. Formations (here and in Figures 5–7): P_3*iv* Ivakinsky, T_1*sv* Syverminsky, T_1*gd* Gudchikhinksy, T_1*hk* Khakanchansky, T_1*tk* Tuklonsky, T_1*nd* Nadezhdinsky, T_1*mr* Morongovsky. Subscript indexes 1,2,3 mean lower, middle and upper subformations, respectively. Sample number is the depth in borehole OB-36, meters.

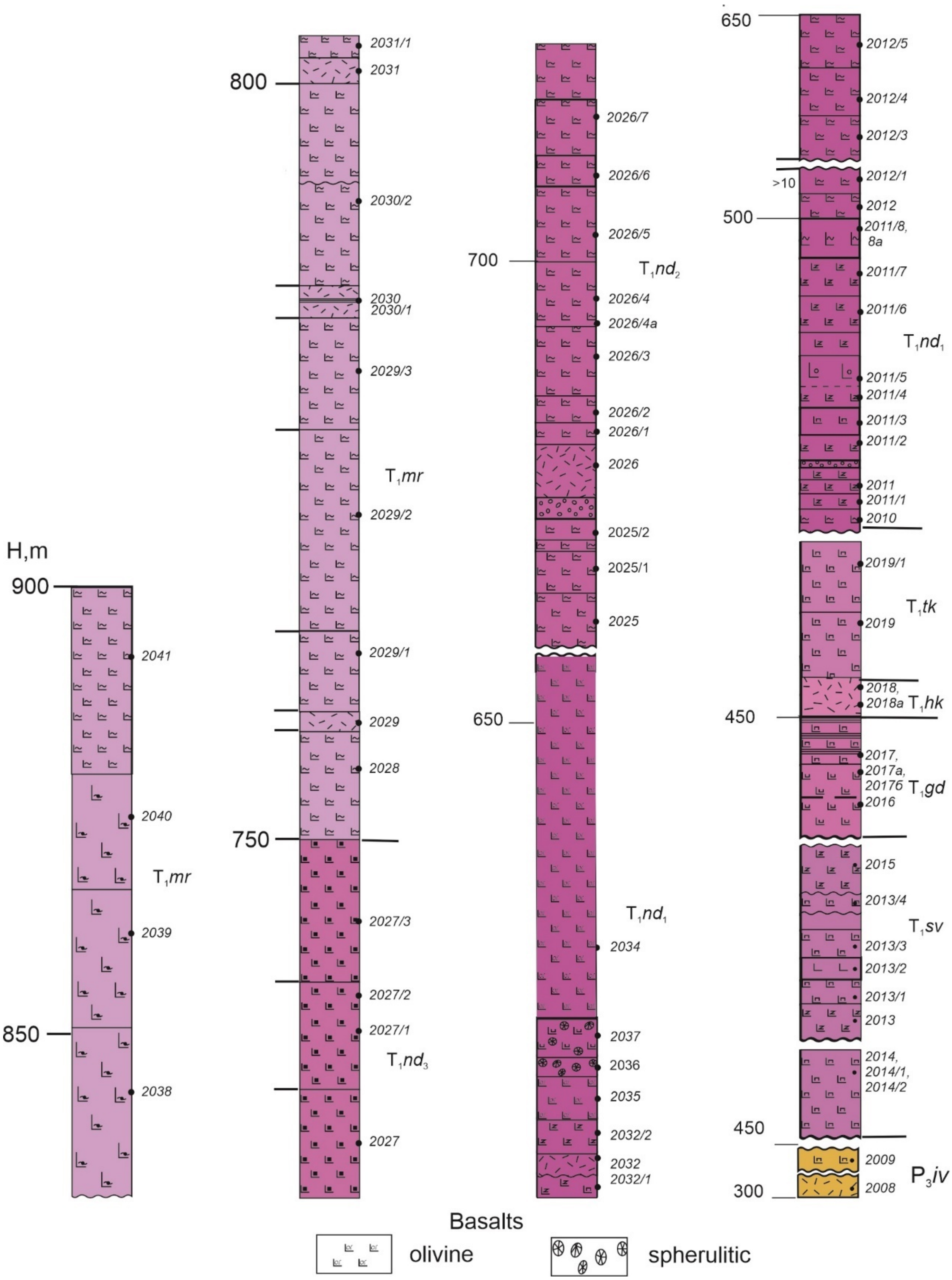

Figure 5. Volcanic section in the Khikey River valley, Captions in Figures 2 and 4.

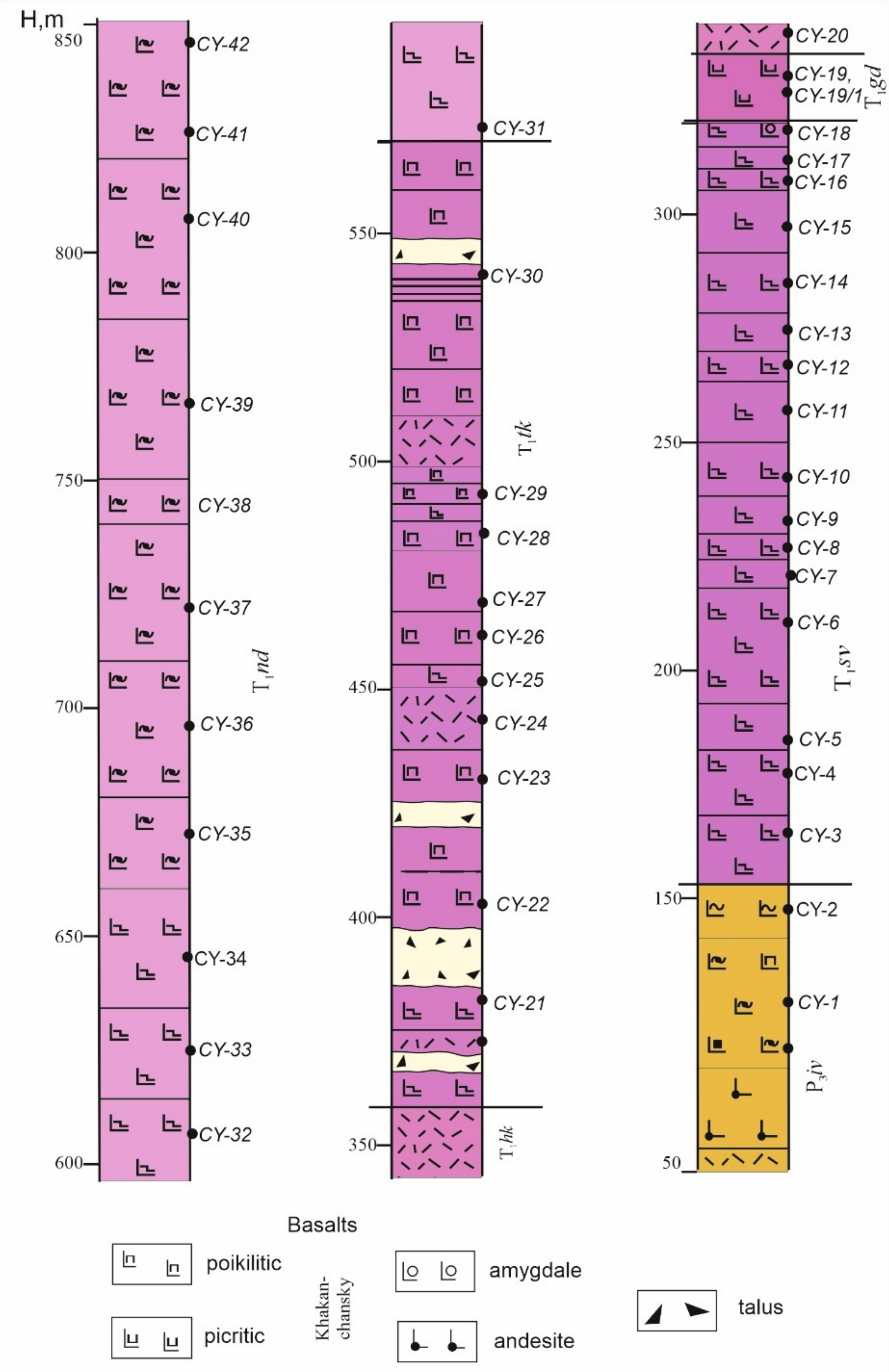

Figure 6. The structure of the volcanic sequence in Mount Sunduk. Captions in Figure 4. H, m—absolute altitude in meters.

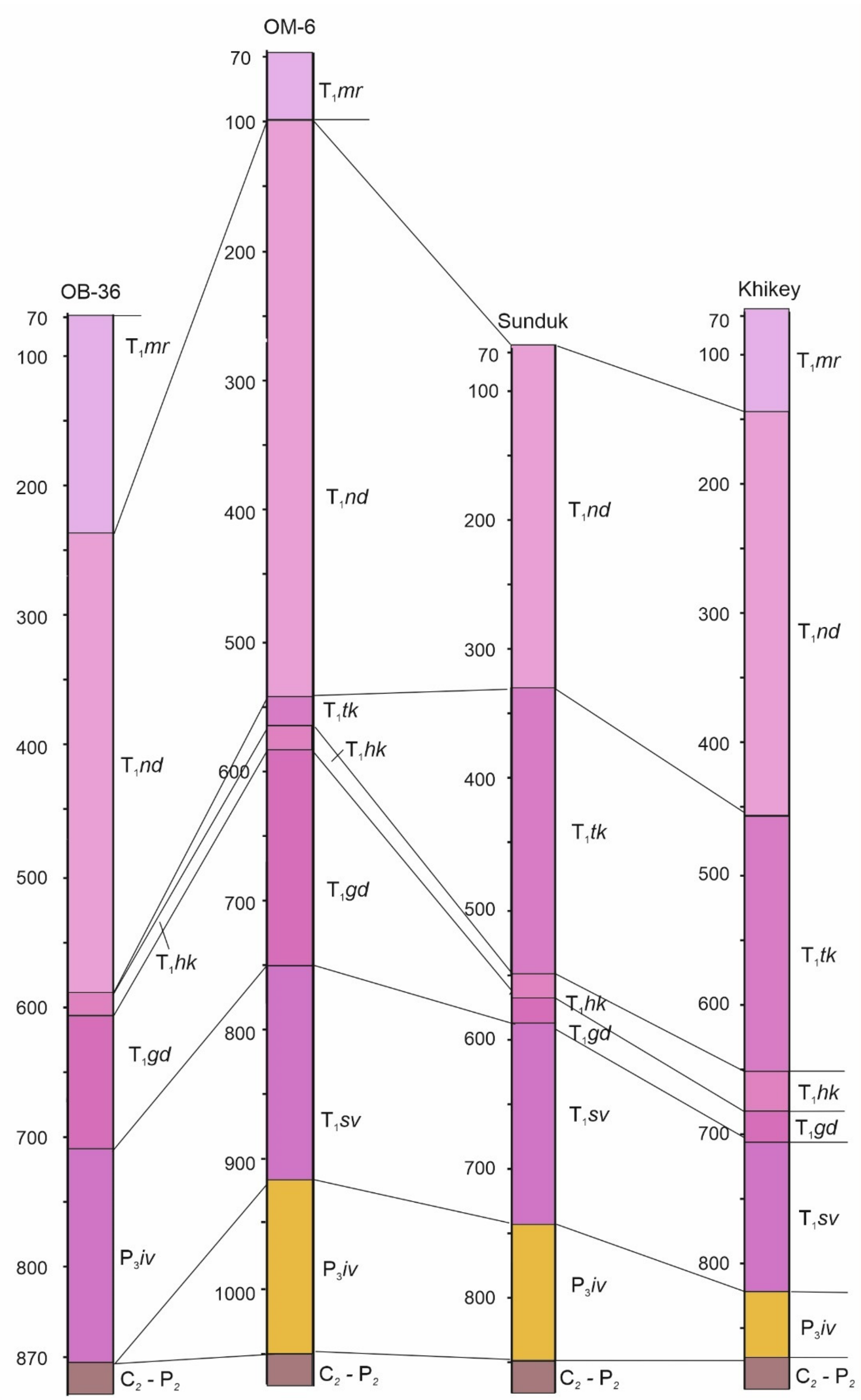

Figure 7. Correlation of volcanic sequences within the Norilsk area.

Table 2. Representative volcanic rock compositions in borehole OB-36.

Component	No	1	2	3	4	5	6	7	8	9
	Depth, m	**69.5**	**221.8**	**273.8**	**289**	**583.5**	**588**	**669**	**745**	**845**
	Formation	**mr**	**mr**	**nd $_3$**	**nd $_2$**	**nd$_1$**	**hk**	**gd $_2$**	**sv**	**sv**
SiO_2		49.43	50.87	52.16	53.08	53.04	55.23	47.36	51.65	51.58
TiO_2		1.15	1.11	1.06	1.05	0.99	1.01	1.25	1.89	1.94
Al_2O_3		16.38	16.27	15.08	15.31	15.49	17.07	7.98	15.54	16.60
Fe_2O_3		12.01	10.57	10.70	10.50	9.82	9.55	13.74	11.63	11.80
MnO		0.22	0.22	0.15	0.20	0.19	0.23	0.20	0.19	0.25
MgO		7.96	6.37	6.09	5.85	5.86	7.40	21.48	7.30	6.30
CaO		10.18	11.18	10.04	9.81	10.90	3.13	6.22	7.29	8.26
Na_2O		1.93	2.11	2.12	2.24	2.13	3.50	1.08	3.04	2.33
K_2O		0.25	0.69	1.15	1.30	1.12	1.57	0.28	0.77	0.52
P_2O_5		0.17	0.14	0.14	0.14	0.13	0.12	0.09	0.21	0.30
Sc		39.2	32.0	33.15	33.40	34.99	31.65	21.69	30.79	28.97
V		306	239	260	246	245	221	247	245	231
Co		51.5	43.3	40.8	40.2	36.1	40.2	107	45.5	38.7
Ni		128	64.0	33.4	38.5	29.2	94.9	1261	62.1	45.3
Cu		136	107	115	92.9	36.5	51.4	108	25.6	31.8
Zn		101	145	129	122	120	136	126	123	132
Rb		5.67	9.01	26.8	39.8	39.2	49.2	9.73	18.2	3.51
Sr		78.7	287	257	243	271	263	175	407	436
Y		25.0	23.71	24.7	26.1	26.0	23.9	12.7	24.0	27.7
Zr		98.0	131	141	146	142	116	70.6	151	212
Nb		5.33	8.38	9.48	9.05	9.42	9.76	5.39	11.07	14.3
La		10.5	18.1	20.9	21.1	22.2	18.1	5.42	16.8	27.2
Ce		23.2	37.2	43.1	42.7	44.3	40.9	14.1	37.9	55.4
Pr		2.99	4.55	5.15	5.23	5.44	4.73	1.98	4.72	6.87
Nd		13.6	19.0	21.1	21.8	22.4	18.8	9.43	20.7	28.4
Sm		3.57	4.15	4.42	4.73	4.82	3.98	2.54	4.80	6.03
Eu		1.15	1.22	1.25	1.27	1.23	1.11	0.89	1.73	2.05
Gd		4.17	4.35	4.56	4.92	4.79	4.19	2.79	5.04	6.14
Tb		0.71	0.69	0.72	0.78	0.74	0.67	0.43	0.80	0.93
Dy		4.59	4.49	4.66	4.95	4.75	4.47	2.56	4.81	5.57
Ho		0.95	0.90	0.93	1.01	0.94	0.88	0.50	0.91	1.09
Er		2.76	2.65	2.65	2.95	2.74	2.58	1.28	2.48	2.99
Tm		2.71	2.56	2.73	2.78	2.65	2.59	1.09	2.21	2.73
Yb		0.40	0.37	0.38	0.41	0.38	0.37	0.17	0.34	0.41
Lu		0.41	0.37	0.39	0.41	0.40	0.36	0.15	0.31	0.39
Hf		2.64	3.36	3.65	3.96	3.65	3.09	1.86	3.71	5.08
Ta		0.33	0.51	0.58	0.56	0.60	0.64	0.34	0.61	0.81
Pb		2.22	12.32	6.97	7.46	7.52	4.85	3.70	4.47	15.45
U		0.64	0.94	1.07	1.09	1.12	1.45	0.35	0.49	0.76

Note. Here and in Table 3 oxides are in wt.%, elements in ppm. Formations: mr—Morongovsky; nd—Nadezhdinsky; kh—Khakanchansky; gd—Gudchikhinsky; sv—Syverminsky, iv—Ivakinsky. $_{1,2,3}$—lower, middle, and upper subformations, respectively.

The rocks of the *Gudchikhinsky Formation* (T_1gd) are located stratigraphically above the basalts of the Syverminsky Formation and are separated from them by psammite tuff (0.5 m). The rocks of this Formation have a melanocratic appearance compared to the other Formations, due to the altered olivine. This Formation consists of three subformations in the Norilsk area [26,35] represented by olivine basalts, picrites, and glomeroporphyritic basalts, respectively. The rocks of the lower and upper subformations are absent in this section. Only the picrites and picritic basalts of the middle subformation occur. A total of 17 flows form this section. Their thickness varies from 30 m in the lower part of the section to 4–5 m in the upper one. The total thickness of the Formation is 105 m.

Table 3. Representative volcanic rock compositions in the Khikey River valley.

Component	Number								
	1	2	3	4	5	6	7	8	9
	Sample Number								
	2009	2013	2017b	2018-1	2019	2025/1	2026/4	2029	2030/2
	Formation								
	iv	sv	gd 2	hk	tk	nd	nd	mr	mr
SiO_2	52.64	53.90	46.67	57.23	50.96	52.00	50.41	49.20	50.67
TiO_2	2.19	1.83	1.10	0.98	0.96	1.08	1.13	0.99	1.08
Al_2O_3	15.02	16.08	8.18	16.87	16.30	16.12	15.15	15.23	15.81
FeO	11.25	9.00	13.95	6.62	9.97	10.83	11.21	10.87	11.22
MnO	0.17	0.17	0.21	0.11	0.20	0.17	0.24	0.17	0.22
MgO	5.48	5.08	22.5	4.35	8.49	6.29	7.73	9.32	7.56
CaO	7.00	9.19	6.19	9.88	11.00	10.62	8.95	10.23	11.38
Na_2O	3.37	3.77	0.74	1.48	1.77	2.03	2.98	1.63	1.99
K_2O	2.25	1.06	0.14	1.50	0.65	0.71	1.16	2.15	0.39
P_2O_5	0.19	0.25	0.09	0.17	0.09	0.09	0.17	0.15	0.11
Total	99.2	100.3	99.8	99.2	100.4	99.9	99.7	99.9	100.4
Rb	76.26	25.20	8.23	56.19	12.08	11.96	33.59	122	10.84
Ba	1110	385	35.6	322	411	292	357	155	121
Th	2.40	3.11	0.83	5.83	0.79	3.45	2.12	1.68	1.32
U	0.55	0.77	0.22	2.09	0.19	0.87	0.70	0.44	0.47
Nb	13.65	14.14	4.65	11.93	3.21	8.56	5.95	4.71	4.33
Ta	0.87	0.87	0.29	0.78	0.21	0.54	0.37	0.30	0.27
La	21.5	24.8	5.75	31.6	6.69	16.7	11.9	11.6	7.92
Ce	47.7	49.2	13.9	59.1	14.4	35.0	24.9	23.0	17.8
Pb	4.87	5.03	1.39	11.33	1.98	3.89	2.63	1.57	2.77
Pr	6.06	6.36	2.00	6.71	1.94	4.37	3.22	2.96	2.39
Nd	26.6	28.0	9.48	26.8	9.01	18.3	14.3	13.3	11.3
Sr	692	239	127	129	322	263	304	161	190
Sm	6.00	6.22	2.57	5.44	2.44	4.22	3.50	3.19	3.04
Zr	209	209	70.4	146	66.5	143	107	90.8	88.4
Hf	4.87	5.04	1.82	3.54	1.78	3.58	2.83	2.40	2.33
Eu	1.95	1.97	0.86	1.51	1.00	1.21	1.10	1.06	1.04
Ti	11898	10710	6590	6389	5795	6507	6894	6174	6618
Gd	6.26	6.20	2.85	5.20	2.92	4.63	4.15	3.78	3.76
Tb	0.93	0.98	0.46	0.77	0.50	0.72	0.70	0.62	0.63
Dy	5.76	5.94	2.71	4.94	3.35	4.70	4.56	4.13	4.31
Ho	1.11	1.12	0.52	0.96	0.67	0.97	0.94	0.85	0.89
Y	29.36	29.98	13.77	24.90	18.03	25.86	24.91	23.07	23.56
Er	3.06	3.16	1.42	2.41	1.97	2.70	2.70	2.50	2.64
Yb	2.68	2.85	1.18	2.66	1.87	2.68	2.69	2.43	2.44
Tm	0.42	0.41	0.18	0.37	0.28	0.39	0.39	0.35	0.38
Lu	0.39	0.42	0.16	0.36	0.28	0.39	0.39	0.35	0.39
Ni	53.6	37.4	1193	72.4	136	65.3	104	105	139
Cu	73.6	40.3	106	43.1	115	90.1	120	61.3	118
Zn	121	94.9	110	94.9	82.5	94.8	115	116	100
Co	209	209	70.4	146	66.5	143	107	90.8	88.4

Note. 2—middle subformations.

The Khakanchansky Formation (T_1hk) lies on the picrites of the Gudchikhinsky Formation and consists of tuffs. T_1hk is a marker horizon in the Norilsk district. It is 13 m thick and has a single tuff horizon, which is heterogeneous in structure. The dark-grey tuffs, with a distinctive layered texture of the pelitic dimension, dominate.

The Nadezhdinsky Formation (T_1nd) overlays the tuffs of the Khakanchansky Formation. It comprises high-thickness individual flows (up to 47 m). This Formation has the highest thickness (444 m) compared to the other Formations in this section. It includes 30 basalt flows and one tuff horizon, with a thickness of 1.8 m. The rocks of the Nadezhdinsky Formation are dark-grey and have a porphyric structure. This Formation was previously divided into subformations, on the basis of the textural and structural features of the rocks [35]. The lower subformation includes porphyritic (often olivine-porphyritic) and tholeiitic basalts; the middle includes plagiporphyritic basalts, and the upper one consists of glomeroporphyritic basalts. In the section of the borehole OV-36, this division is not clear. Therefore, the subdivision into subformations is based on the analytical data and will be discussed below.

The Morongovsky Formation (T_1*mr*) completes the section of volcanic rocks penetrated by the borehole OV-36. In addition to the basalts, pyroclastic rocks comprising 35% of the section play a significant role in the composition of the Morongovsky Formation in the Vologachan syncline, which differs from the other sections around the Norilsk area. The thickness of this Formation is about 70 m (its upper part is eroded). It consists of three 15–17 m thick, dark-grey basalt flows, often with a fluid texture and an aphyric structure, and two tuff horizons of 10 m and 17 m.

The intrusive body of gabbro–dolerites intrudes the Nadezhdinsky Formation. It is 30 m thick (according to the borehole OB-36). Its morphology is unclear; it is assumed that it is a sill.

4.2. Volcanic Sequence in the Khikey River Valley

The section of the volcanic rocks in the Khikey River valley is located in the periclinal closure of the Khantajsko–Rybninsky swell in the eastern part of the Norilsk district (Figure 2). The formations distinguished in the borehole OB-36 have been found in this section, as well as the missing Ivakinsky and Tuklonsky Formations.

The rocks of the *I v a k i n s k y* Formation (P_3*iv*) occur on the sediments of the Tunguska series. They are represented by dark-grey–black, fine-grained massive rocks with a porphyric structure. Only one flow, represented by andesite basalts, is exposed on the surface (Tables 3 and S2). Its thickness is 12 m. According to the drilling in this area in the 1990s, the thickness of this Formation is 85 m. The Ivakinsky Formation principally differs from the other Formations by its reverse magnetization, which evidences its Late Permian age [35,39]. The other Formations were formed in the Early Triassic, according to their direct magnetization. The *Syverminsky Formation* (T_1*sv*) consists of numerous thin flows (5–8 m) of greenstone basalts with a tholeiitic structure, which have been actively altered due to the presence of glass in the rocks. They are well distinguished in the relief due to the intensive destruction of the thick amygdale zones (1–3 m). The Formation includes 17 flows with a total thickness of 78 m. *The Gudchikhinsky Formation* (T_1*gd*) has a low thickness in this area of 10–12 m. It is represented by two stratified flows of picritic basalts belonging to the middle subformation. The flows contain a layered structure fixed by horizons differently resistant to weathering: dense, 10–15 cm thick, and soft, 5–7 cm thick. A similar structure of the rocks in the Gudchikhinsky Formation was recorded earlier in the Iken River valley [6]. The rocks of this formation have a very low thickness of the amygdale zones (first centimeters).

The tuffs *of the Khakanchansky Formation* (T_1*hk*) covers the rocks of the Gudchikhinsky Formation. They are represented by psammitic tuffites and, in rare cases, by tuff-breccias. Their thickness is 7–8 m. The basalts *of the Tuklonsky Formation* (T_1*tk*), that are absent in the Vologochan syncline, form a sequence in 150-160 m in the Khikey River valley. They are represented by light greenish-grey tholeiitic rocks of a massive texture. The rocks are intensely chloritized, and they have the specified green coloring. They look like the Syverminsky basalts, but, as shown below, they differ significantly in their composition. *The Nadezhdinsky Formation* (T_1*nd*) lies above the Tuklonsky Formation, and its lower part is also composed of tholeiitic basalts. Therefore, the boundary between these Formations often is fixed only on the basis of the chemical composition of the rocks. The central and upper parts of the Nadezhdinsky.

Formation are composed of porphyric and aphyric basalts, while the roof comprises glomeroporphyric basalts (T_1nd_3). The latter is the most typical of the upper subformation. The boundary between the lower and middle subformations (T_1nd_1 and T_1nd_2) is unclear. The rock compositions usually determine it. Generally, the Nadezhdinsky Formation is characterized by thick flows in the middle and upper subformations (30–40 m) and an overall high level of thickness (up to 480 m). The lower subformation comprises 11 flows (8–15 m thick), while the middle subformation consists of 10 flows of 25–30 m thick (mostly porphyric basalts), and the upper subformation combines 3 flows of glomeroporphyric basalts (12–15 m thick).

The Morongovsky Formation (T_1mr), lying on the Nadezhdinsky Formation, forms the top of this section and armors the mountain surfaces. It is composed of porphyric and, less frequently, aphyric basalts with an average thickness of 15 m. In contrast to the Vologochan syncline, the tuffs are absent in this formation. The total thickness of the formation is about 80 m, and its upper part has been destroyed by erosion.

A gabbro–dolerite sill (Figure 2) lies at the base of the section, at the boundary of the Tunguska Series and the Ivakinsky Formation. Its affiliation to the intrusive complex will be considered according to its geochemical features.

4.3. Volcanic Sequence in Mount Sunduk

As mentioned above, this section was described by Lightfoot et al. earlier [36]. We give only its brief description. The volcanic section in Mount Sunduk comprises the rocks of the six lower Formations, i.e., Ivakinsky, Syverminsky, Gudchikhinsky, Khakanchansky, Tuklonsky, and Nadezhdinsky (Figure 6). It is 800 thick. The *I v a k i n s k y* and *S y v e r m i n s k y F o r m a t i o n s* are similar to these Formations in the Norilsk syncline. They include andesite basalts and tholeiitic basalts, respectively. The *G u d c h i k h i n s k y F o r m a t i o n* consists of one flow of picrites, as described in [40]. The Khakanchansy Formation (10 m thick) has a complex structure and consists of several horizons of tuffs and tuffites, varying in the size of the fragments from breccia to psephitic tuffs. The Tuklonsky Formation is the most interesting in this section. First, it has the biggest thickness here compared with the other parts of the Norilsk area, and second, it comprises a layered flow. The latter consists of interlayers with a different olivine content, which has a dendritic morphology in some interlayers [6]. Olivine poikilophitic basalts form the other 15 flows. This Formation includes three tuff horizons. The Nadezhdinsky Formation consists of 12 tholeiitic flows, and their average thickness is 25–30 m.

4.4. Variations in Tuff-Lavas Structure

Figure 7 compares the three studied volcanic sections, and one in the Norilsk syncline described earlier [41]. They are located in sections I-I and II-II (Figure 2). There are variations in the structure of the tuff–lava sequence from the OB-36 to Mount Sunduk, i.e., from west to east (from the Vologchan syncline to the Tunguska syneclise). Firstly, the Ivakinsky Formation is partially absent in the Vologochan syncline, but it appears in the Norilsk syncline, characterized by the greatest thickness (150 m), which is reduced in the Tunguska syneclise (60 m). The Syverminsky Formation is the most stable in thickness and composition. The Gudchikhinky Formation dramatically changes in these parameters. It is widespread in the Norilsk syncline and almost disappears east of it.

On the contrary, the Tuklonsky Formation has the greatest thickness in Mount Sunduk (220 m) and pinches out to the west, and it is absent in the Vologichan syncline (borehole OB-36). The Khakanchansky Formation varies insignificantly. The Nadezhdinsky Formation tends to decrease from west to east, but we cannot estimate a thickness change because it is eroded in some sections. Thus, the structure of the tuff–lavas sequence varies within the Norilsk area from the Yenisey–Khatanga trough Vologocahn syncline to the Tunguska syneclise.

4.5. Geochemical Features of Igneous Rocks

The chemical compositions of the studied igneous rocks show a large range of their varieties—from the picrites to basaltic andesite and the subalkaline basalts (Tables 2–4 and S2–S4). Thus, the SiO_2 contents vary from 42.8 wt. to 57.3 wt.%. The SiO_2 concentrations vary within the Formations and between them. The lowest MgO concentrations, 3.4 wt.% and 4.4 wt.%, are found in the tuffs of the Morongovsky and Khakanchansky Formations, respectively, and the rocks of the Syverminsky Formation. The rocks of the other Formations are characterized by a narrow range of MgO contents (6–8 wt.%), with a tendency of the MgO increasing towards the top of the sections from the Nadezhdinsky to Morongovsky Formations.

Table 4. Representative volcanic rock compositions in Mount Sunduk.

Component	1	2	3	4	5	6	7	8	9	10
	CY-1	**CY-3**	**CY-19**	**CY-20**	**CY-24**	**CY-25**	**CY-26**	**CY-30**	**CY-35**	**CY-36**
	iv	**sv**	**gd** $_2$	**hk**	**tk**	**tk**	**tk**	**tk**	**nd** $_1$	**nd** $_2$
SiO_2	50.98	53.66	47.22	53.81	49.98	53.43	51.36	47.85	52.96	53.09
TiO_2	2.41	1.66	1.71	1.02	0.99	0.99	0.94	0.60	0.96	0.96
Al_2O_3	17.26	15.35	8.79	18.06	15.77	14.19	15.46	13.42	15.08	15.62
FeO	11.26	9.86	14.5	9.20	10.9	10.3	9.83	10.8	9.64	9.14
MnO	0.15	0.14	0.25	0.14	0.18	0.19	0.17	0.18	0.17	0.16
MgO	4.76	6.06	17.98	6.54	8.69	8.56	8.25	13.48	7.19	6.64
CaO	6.26	9.50	8.32	9.25	10.06	5.31	10.5	12.2	8.42	10.2
Na_2O	5.19	2.51	0.63	1.00	2.55	1.38	2.76	1.09	3.40	2.87
K_2O	0.52	0.77	0.08	0.71	0.88	4.84	0.94	0.19	1.78	0.91
P_2O_5	0.31	0.18	0.14	0.14	0.08	0.13	0.04	0.07	0.15	0.17
Rb	12.5	18.0	2.2	19.6	24.5	106.4	22.7	3.3	52.6	35.6
Ba	438	428	33	128	369	1171	479	99	718	348
Th	2.35	4.21	0.79	3.92	0.76	4.64	0.68	0.41	3.12	3.55
U	0.46	1.00	0.20	0.88	0.15	1.05	0.15	0.08	0.86	0.78
Nb	18.1	16.4	7.24	8.19	3.01	11.33	3.08	1.81	7.07	7.94
Ta	1.03	0.97	0.47	0.54	0.19	0.77	0.19	0.11	0.44	0.50
La	30.7	26.9	7.7	19.8	5.4	10.0	7.3	3.4	16.0	17.9
Ce	63.6	54.6	18.2	35.8	11.2	25.7	14.1	6.8	32.1	34.8
Pb	2.11	5.01	0.18	5.43	0.48	4.85	0.71	0.88	3.94	4.11
Pr	7.67	6.47	2.63	4.22	1.59	3.49	1.83	0.97	3.86	4.18
Nd	35.1	28.6	14.2	19.1	8.3	16.4	9.0	5.1	17.0	18.3
Sr	418	586	143	178	423	69	405	174	596	456
Sm	7.49	6.29	3.97	4.19	2.44	4.07	2.38	1.48	3.75	4.10
Zr	241	213	109	153	61	127	63	37	114	130
Hf	5.27	4.67	2.67	3.40	1.55	3.10	1.53	0.98	2.78	3.15
Eu	2.37	1.81	1.35	1.28	0.92	0.98	0.96	0.59	1.05	1.12
Ti	17,353	11,364	12,075	5846	5283	5960	6753	3578	6559	6764
Gd	7.09	6.01	4.24	4.14	2.79	4.08	2.70	1.77	3.70	3.96
Tb	1.03	0.88	0.62	0.63	0.48	0.66	0.44	0.28	0.58	0.62
Dy	6.74	5.76	4.01	4.25	3.43	4.45	3.13	2.05	3.95	4.36
Ho	1.28	1.08	0.72	0.85	0.68	0.89	0.63	0.42	0.77	0.89
Y	32.35	27.28	17.96	21.54	17.16	22.60	15.96	10.40	20.08	21.97
Er	3.58	3.03	1.93	2.44	2.02	2.67	1.83	1.25	2.32	2.58
Tm	0.51	0.41	0.24	0.35	0.27	0.38	0.25	0.17	0.32	0.36
Yb	3.32	2.79	1.61	2.40	1.89	2.60	1.73	1.18	2.25	2.50
Lu	0.49	0.40	0.21	0.36	0.27	0.36	0.26	0.17	0.32	0.36
Ni	41	86	1042	114	95	81	95	243	17	46
Cu	31	36	113	78	84	96	85	47	15	62
Zn	114	111	41	81	36	92	46	73	99	91
Co	41	39	103	43	48	40	47	74	41	42

Note: $_{1,2}$ mean lower, middle subformations.

The MgO variations in the volcanic sequence in the Vologochan syncline (Tables 2 and S1) are shown in Figure 4, which demonstrates the distinct difference between its upper, more homogeneous, and lower stratigraphic parts. Furthermore, the lower part of the section is enriched in TiO_2 concentrations (from the Syverminsky to the Gudchikhinsky Formations, 1–1.9 wt.% TiO_2), whereas the upper part (from the Tuklonsky Formation) shows consistently low concentrations (0.8–1.3 wt.% TiO_2).

To study the variations in the rock compositions along the strike, we plotted the geochemical data from four sections, including the Vologochan syncline (borehole OB-36, the previously studied Norilsk syncline (borehole OM-6, [41]), Mount Sunduk (Tables 4 and S2), and the Khalil River valley, on Harker diagrams (Figures 7–9). We grouped the analytical data for the best view and plotted them separately. The first group includes the Ivakinsky, Syverminsky, and Gudchikhinsky Formations; the second group combines the Khakanchansky and Tuklonsky Formations; and the Nadezhdinsky Formation represents the third group. The data on the Morongovsky Formation were obtained only for the Vologochan syncline, so the variations in its composition could not be traced here. Information on the composition of the Morongovsky and Mokulaevsky Formations has been published previously [6,31] and indicates that their composition is consistent.

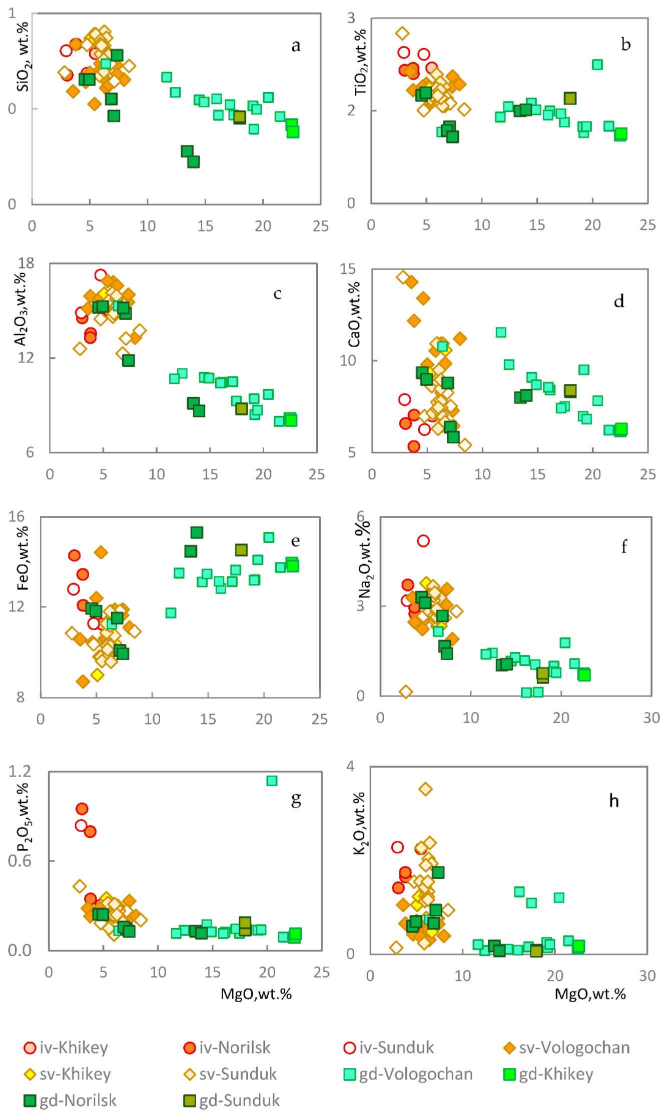

Figure 8. Diagrams MgO vs. SiO_2 (**a**), TiO_2 (**b**), Al_2O_3 (**c**), CaO (**d**), FeO (**e**), Na_2O (**f**), P_2O_5 (**g**), and K_2O (**h**) for the Ivakinsky, Syverminsky, and Gudchikhinsky Formations.

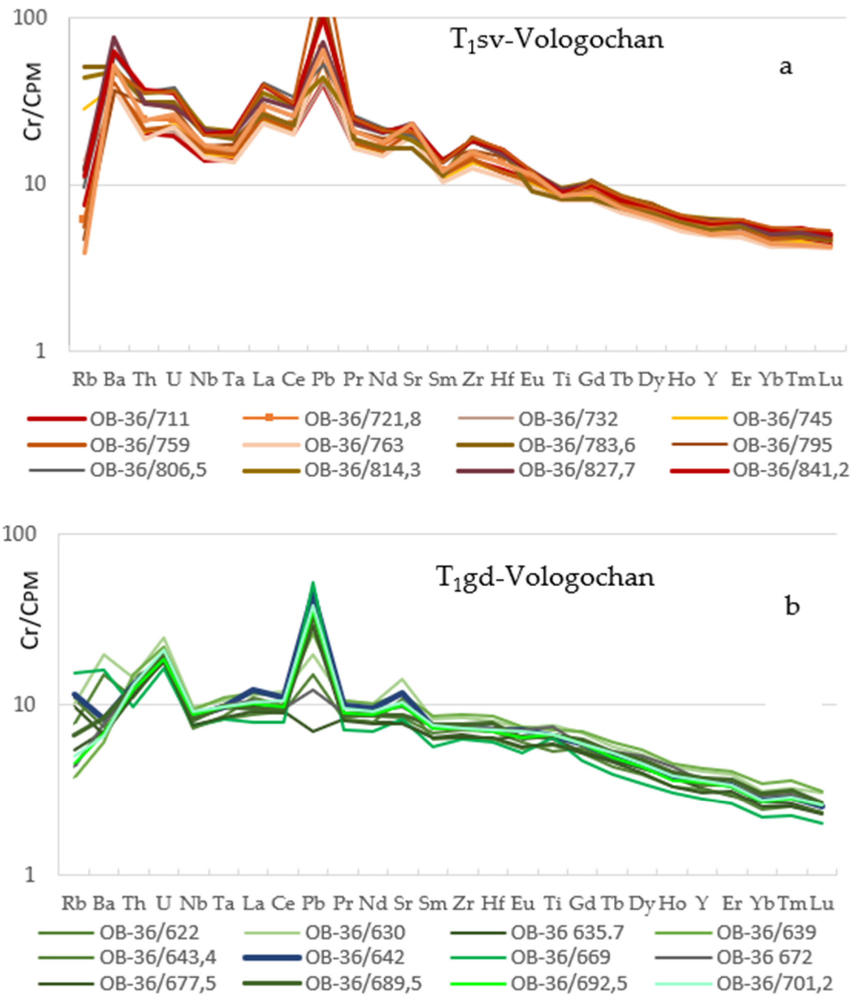

Figure 9. Spider diagrams for rocks of the Syverminsky (**a**) and Gudchikhinsky (**b**) Formations in the Vologochan syncline. Here and in Figures 10, 14, 15, 17, 21 normalized to primitive mantle [42].

4.5.1. The Rock Compositions of the Ivakinsky, Syverminsky, and Gudchikhinsky Formations

As noted above, the Ivakinsky Formation is absent in the Vologachan syncline in the borehole OB-36, so it has been analyzed in the other sections. On the basis of the limited number of analyses, we conclude that the rocks are very similar in composition of the major oxides: SiO_2, FeO, CaO, Na_2O, K_2O, and P_2O_5 (Figure 8a–h). Only the rocks in the Mount Sunduk section are slightly enriched in TiO_2 and Al_2O_3 compared with the Norilsk syncline and Khikey River valley (Figure 8b,c). The rocks of the Syverminsky Formation have been studied in more detail, so the comparison of these rocks is more representative. The most distinct difference between the basalts in the Norilsk and Vologachan synclines and Mount Sunduk occurs here: the former rocks are enriched in SiO_2 (Figure 8a) and slightly depleted in iron. They also have a wide range of MgO contents. The rocks of Mount Sunduk are similar to the andesite basalts of the Khikey River valley. The Syverminsky rocks do not differ in the other oxides.

The Ivakinsky and Syverminsky rocks are similar in their patterns and close to these Formations in the Kharaelakh syncline [30]. They contain positive Ba, Pb, Sr, and Zr anomalies and a small negative Ta-Nb (Figure 9a). These rocks are enriched in the light lithophilic elements and depleted in the HREE elements. Thus, the rocks of the Syverminsky Formation have high (La/Yb)n and (Gd/Yb)n ratios, especially the rocks of the Khikey River valley, in comparison with the Norilsk and Mount Sunduk ones (Figure 10a,b).

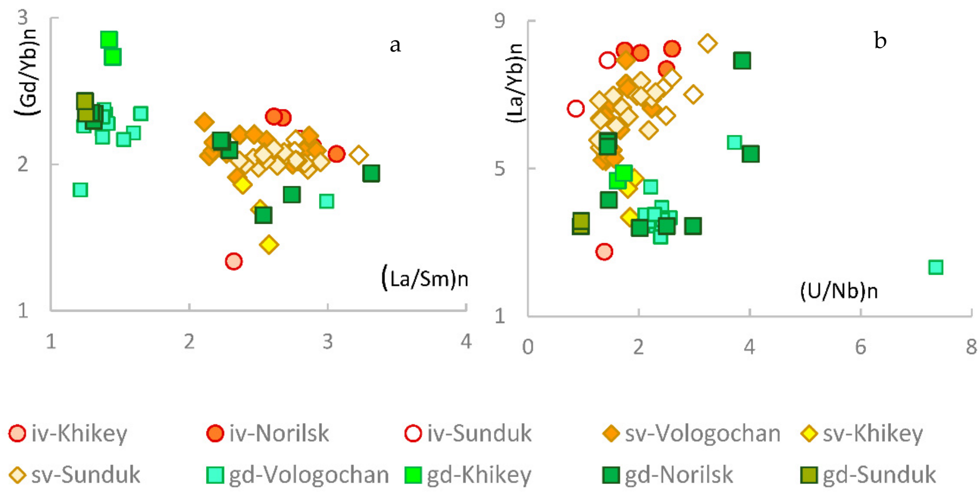

Figure 10. Diagrams (La/Sm)n vs. (Gd/Yb)n (**a**) and (U/Nb)n vs. (La/Yb)n (**b**) for the Ivakinsky, Syverminsky, and Gudchikhinsky Formations.

The Gudchikhinsky Formation consists of basalts in the Norilsk and Vologochan synclines, whereas picritic basalts and picrites dominate in the Mount Sunduk and Khikey River valley, so the MgO changes from 5 to 23 wt.%. Thus, the lower subformation is widespread (T_1gd_1) in the first two sections (comprising two-thirds of the Norilsk section [41], while the middle subformation dominates in the last sections (T_1gd_2). According to our data, the basalts of the Norilsk syncline are distinguished by elevated SiO_2, Al_2O_3, Na_2O, K_2O, and P_2O_5 and lower FeO concentrations (Figure 8a,c,e,f–h), as well as elevated (La/Sm)n and slightly lower (Gd/Yb)n ratios (Figure 10a,b). The composition of the Gudchikhinsky rocks varied significantly in the trace elements, which was shown earlier [40].

4.5.2. The Rock Compositions of the Khakanchansky and Tuklonsky Formations

Figure 11 shows the compositions of these Formations from different volcanic sections. The Tuklonsky Formation consists of basalts and picrites that form different fields of points on the diagrams, due to the MgO variations (Figure 11a–h), ranging in 6–8 wt% and 13–15 wt.%, respectively. The Khakanchnsky tuffs and tuffites demonstrate a range of compositions; they differ from the Tuklonsky rocks in SiO_2 and alkalines (Figure 11a,g,h). These two rock varieties differ in FeO and Na_2O, and P_2O_5 (Figure 11d,g,h), and especially, in the (La/Sm)n, (Gd/Yb)n, and (U/Nb)n ratios (Figure 12a,b).

4.5.3. The Rock Compositions of the Nadezhdinsky Formation

The most significant compositional variations have been established for the Nadezhdinsky Formation. We have analyzed 84 samples in four sections (Figure 13) belonging to the lower and middle subformations. The low MgO content is typical of the Nadezhdinsky Formation, varying from 4.4 to 6 wt.%. These rocks are characterized by low Al_2O_3 and slightly elevated FeO concentrations (Figure 13c,d). There are differences between the rocks from the different sections. The rocks in the Khikey section demonstrate the maximum deviations from those in the Vologochan and Norilsk synclines, and Mount Sunduk. The lower subformaiton of the Nadezhdinsky Formation in this section contains a minimum of TiO_2 (Figure 13b), FeO (Figure 13d), and P_2O_5 (Figure 13h), in comparison with the other rocks of the Norilsk area, while the SiO_2, Al_2O_3, CaO, Na_2O, and K_2O, contents are similar in all of them. Both the lower and middle subformations in the Norilsk syncline comprise a minimum of SiO_2 and Al_2O_3.

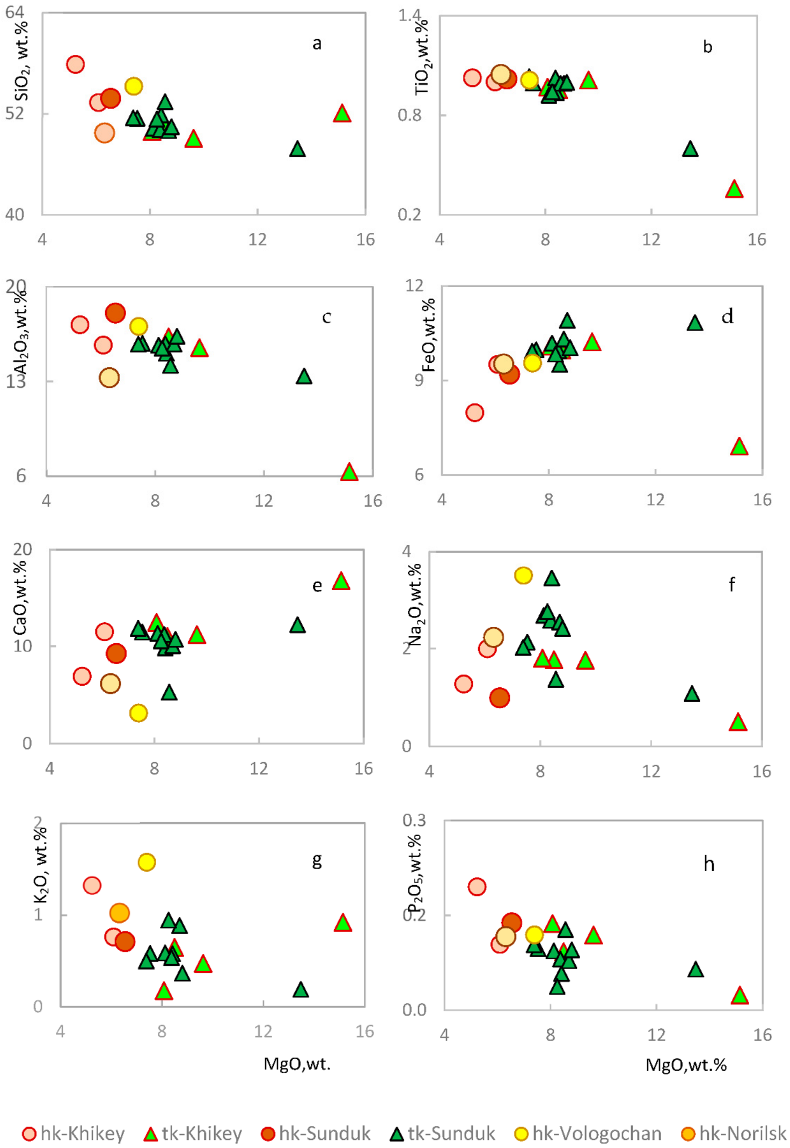

Figure 11. Diagrams MgO vs. SiO_2 (**a**), TiO_2 (**b**), Al_2O_3 (**c**), FeO (**d**), CaO (**e**), Na_2O (**f**), K_2O (**g**), and P_2O_5 (**h**) for the rocks of the Khakanchansky and Tuklonsky Formations.

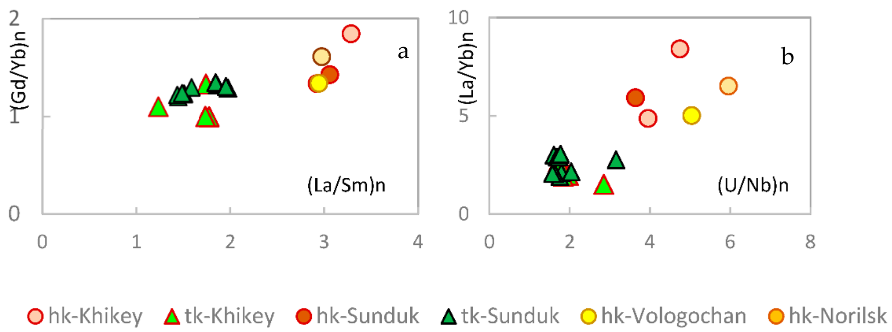

Figure 12. Diagrams (La/Sm)n vs. (Gd/Yb)n (**a**) and (U/Nb)n vs. (La/Yb)n (**b**) for the Khakanchansky and Tuklonsky Formations.

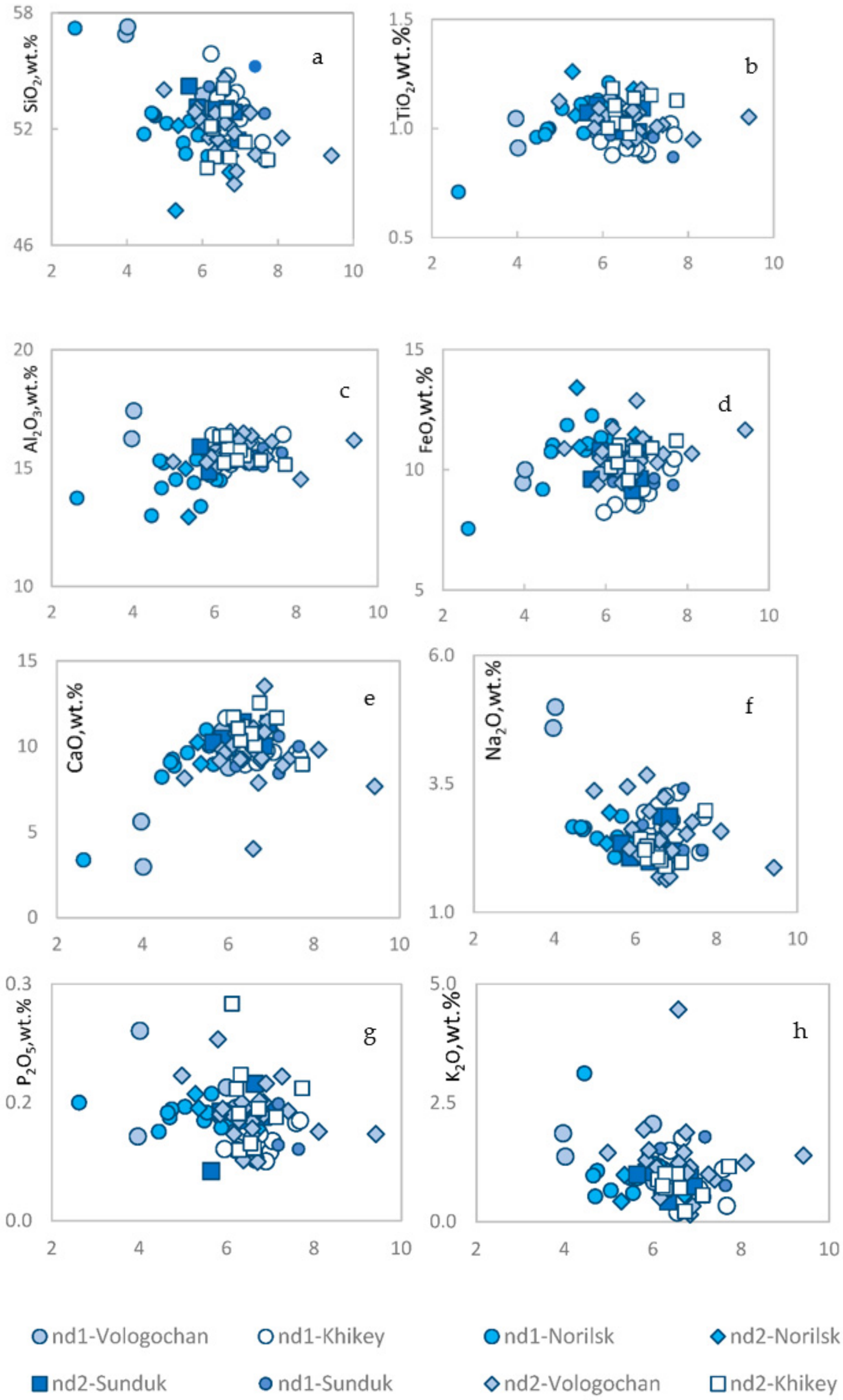

Figure 13. Diagrams MgO vs. SiO_2 (**a**), TiO_2 (**b**), Al_2O_3 (**c**), FeO (**d**), CaO (**e**), Na_2O (**f**), P_2O_5 (**g**), and K_2O (**h**) for the rocks of the Nadezhdinsky Formation.

Figure 14a,b demonstrates the big differences between the Nadezhdinsky rocks in the Khikey River valley and the other sections in terms of the low (La/Yb)n and (Gd/Yb)n ratios, varying from 2 to 4 and 0.9 to 1.1, in contrast to 4 to 6 and 1.2 to 1.4, respectively, in the other rocks. The (La/Sm)n is slightly lower for the Khikey rocks compared with the other rocks.

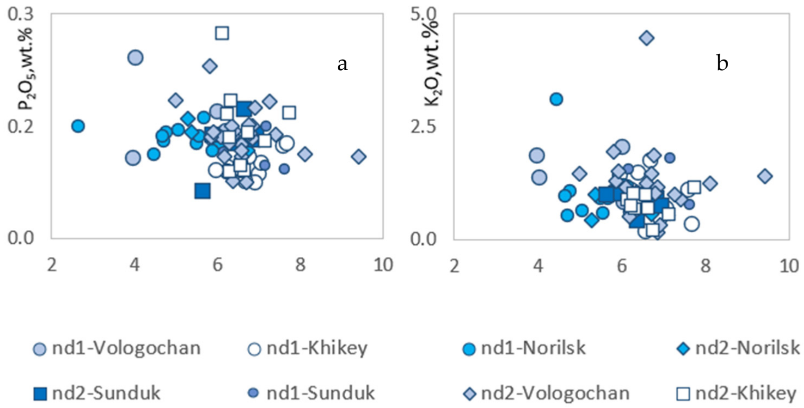

Figure 14. Diagrams (La/Sm)n vs. (Gd/Yb)n (**a**) and (U/Nb)n vs. (La/Yb)n (**b**) for the rocks of the Nadezhdinsky Formation. Captions in Figure 13.

The differences between the trace element contents in the Khakanchansky, Nadezhdinsky, and lower Morongovsky Formations are not evident in the spider diagrams shown in Figure 15. It was suggested [43] that the tuffs of the Khakanchansky Formation could be attributed to the Nadezhdinsky Formation on the basis of their geochemical characteristics. Despite the similar composition of the lower Morongovsky rocks to the Nadezhdinsky basalts in the western part of the Norilsk area, they are different in the east. Taking into account the difference of these rocks in the east and their different location, they could not be combined within one group, as was shown in [6]. So, these rocks, the Khakanchansky, Nadezhdinsky, and lower Morongovsky, should not be distinguished as a transitional series between the OIB and WPB, as was suggested [29], due to their widespread difference in locations.

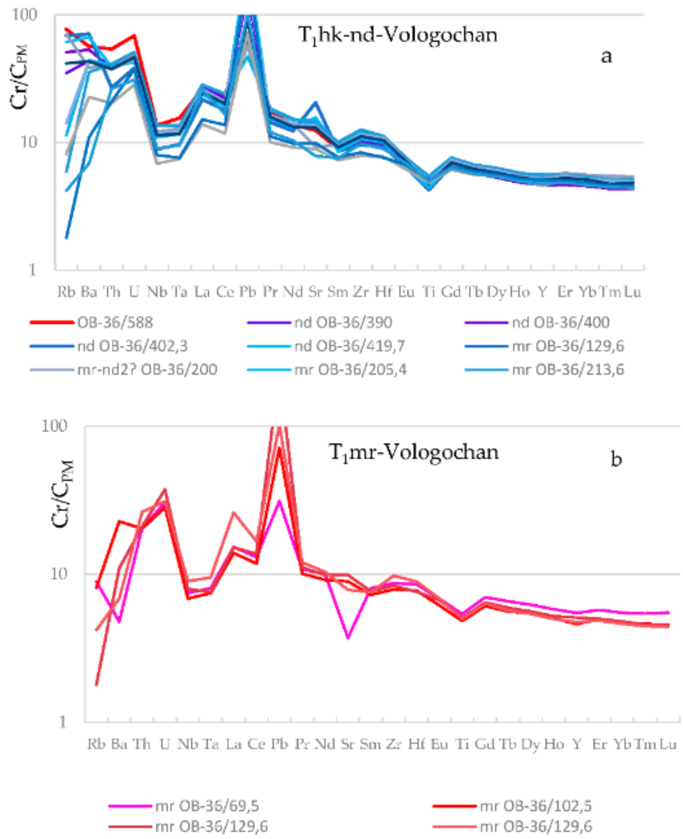

Figure 15. Spider-diagrams for rocks of the Khakanchansky, Nadezhdinsky (**a**), and Morongovsky (**b**) Formations in the Vologochan syncline.

4.5.4. Compositions of Intrusive Rocks

We have found two sills during our study. The first sill is located within the Nadezhdinsky basalts in the borehole OB-36, while the second is exposed in the Khikey River valley. They consist of dark-grey gabbro–dolerites and olivine gabbro–dolerites with massive structures and dolerite textures. Figure 16 shows their compositions in terms of their major components (Tables S2 and S3). The data on the ore-bearing South Pyasinsky intrusion, penetrated by the borehole OB-36 at depths of 1465–1535 m [37], are also plotted in these diagrams.

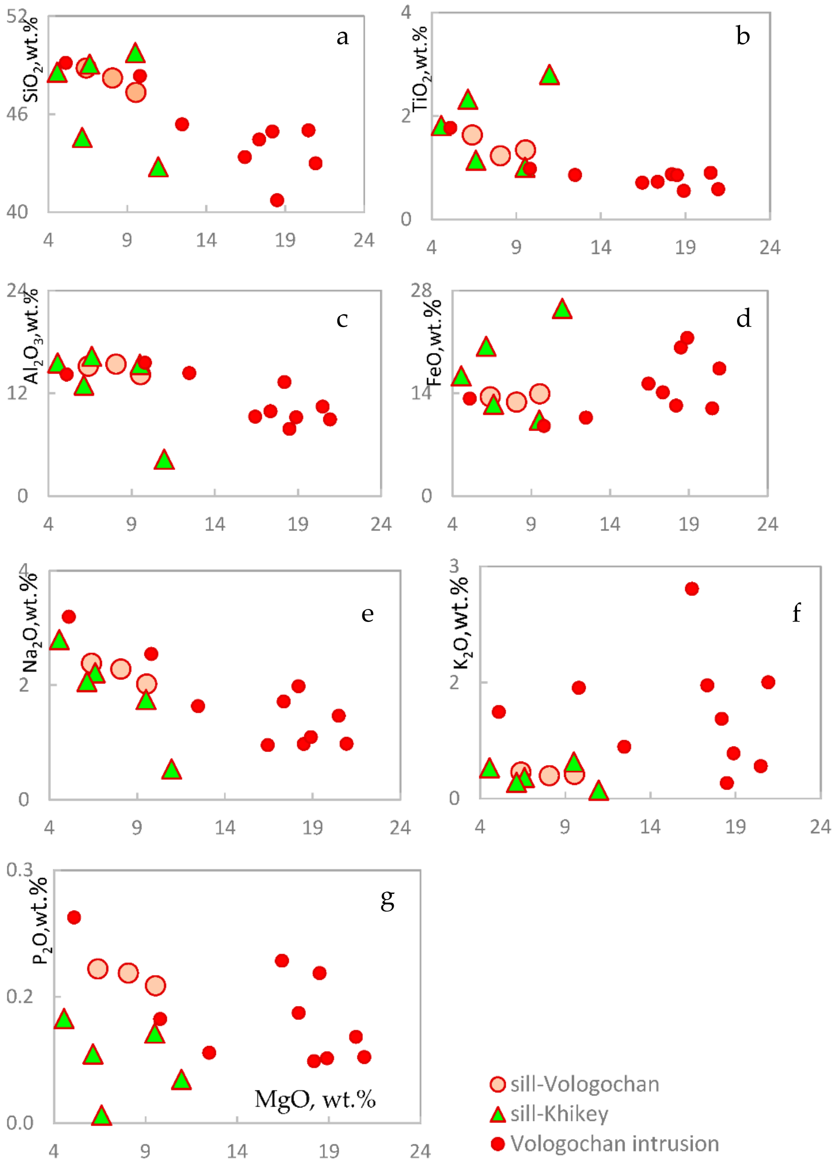

Figure 16. Diagrams MgO vs. SiO_2 (**a**), TiO_2 (**b**), Al_2O_3 (**c**), FeO (**d**), Na_2O (**e**), K_2O (**f**), P_2O_5 (**g**), % for intrusive rocks.

The compositions of the studied rocks indicate a significant homogeneity of the first sill and a heterogeneity of the second one (Figure 16). Although their MgO contents are similar, the concentrations of other oxides are very different. The significant variations in the values of SiO_2 (Figure 16a), TiO_2 (Figure 16b), FeO (Figure 16d), Na_2O (Figure 16e), and P_2O_5 (Figure 16g) are typical of the Khalil River valley sill, although the concentrations of Al_2O_3 and K_2O (Figure 16c,f) are similar. On the contrary, the intrusive body lying in the Vologochan syncline is characterized by the sustained contents of the major oxides.

A comparison of the two studied intrusive bodies with the compositions of the South Pyasinsky intrusion, containing platinum-copper-nickel ores [37], indicates (Figure 16) a significant similarity of the sill from the Vologdachan syncline with the ore-bearing intrusion (excepting the K_2O and P_2O_5). The differences in FeO content are due to the presence of sulfides in the latter body). The intrusion from the Khalil River valley differs significantly from the South Pyasinsky intrusion, except for Al_2O_3.

Despite the proximity of the two intrusive bodies penetrated by the borehole OB-36 in the Vologochan syncline, they are not identical in terms of the trace elements. Although the topology of their patterns is similar (Figure 17), the intensities of the Ta-Nb anomalies are different: it is less manifested in the sill in comparison with the anomaly in the ore-bearing South Pyasinsky intrusion. Therefore, the sill can be conditionally attributed to the Norilsk intrusive complex.

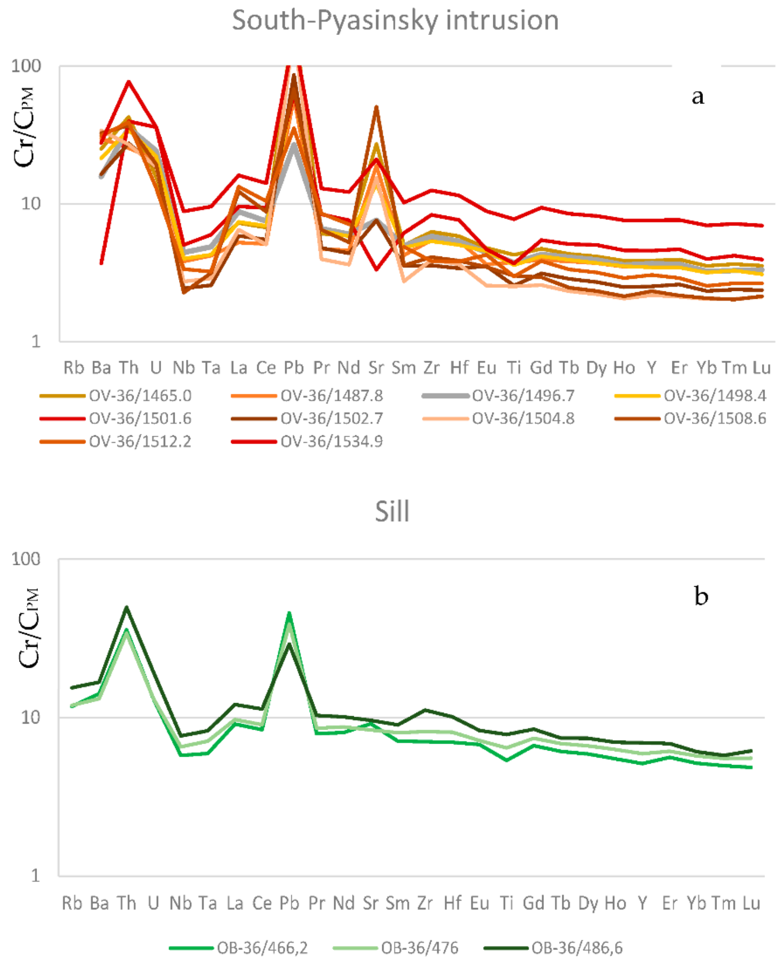

Figure 17. Spider-diagrams for the intrusive rocks in the Vologochan syncline: (**a**) South Pyasinsky intrusion, (**b**) sill.

4.5.5. Metals in Volcanic and Intrusive Rocks

The main metals that make up the main value of the Norilsk ores are palladium and nickel (https://www.nornickel.com/news-and-media/press-releases-and-news/nornickel-announces-consolidated-production-results-for-1h-2022/ [44], accessed on 11 September 2022). Copper, platinum, gold, and silver are also mined in large quantities. In total, 18 elements are extracted from sulfide ores, including the platinum group metals, Co, Zn, and many others.

We have studied the contents of the non–ferrous metals—Ni, Cu, Co, and Zn—in the volcanic and intrusive rocks (Tables 1–3 and S2–S4). These data are grouped by the Formations, similar to how it was done for the major and trace elements (see Section 4.5).

Figure 18 shows the behavior of the two main metals in the volcanic rocks, i.e., copper and nickel. Figure 18a–c demonstrates that the maximum Cu concentrations (up to 170 ppm) are characteristic of high-Mg rocks, namely, the Gudchikhinsky and Tuklonsky Formations (picritic basalts and picrites). There is a correlation between the Cu and MgO contents in the Gudchikhinsky rocks, especially for the rocks with high MgO (over 10 wt.%). There is no such dependence for the Tuklonsky formation, which indicates its saturation with sulfur and the appearance of a sulfide phase. The copper content in the Ivakinsky and Syverminsky rocks, containing 3–7 wt.% MgO, does not exceed 100 ppm and is 40 ppm on average. The greatest range of Cu contents in rocks is typical of the Nadezhdinsky formation, where its concentrations change from 20 ppm to 230 ppm (Figure 18c), forming a continuous series of concentrations. The minimum Cu contents are established in the lower subformation of the Nadezhdinsky formation, which is one of the main characteristics of this subformation. These data were previously interpreted as the Cu removal during the sulfide settling.

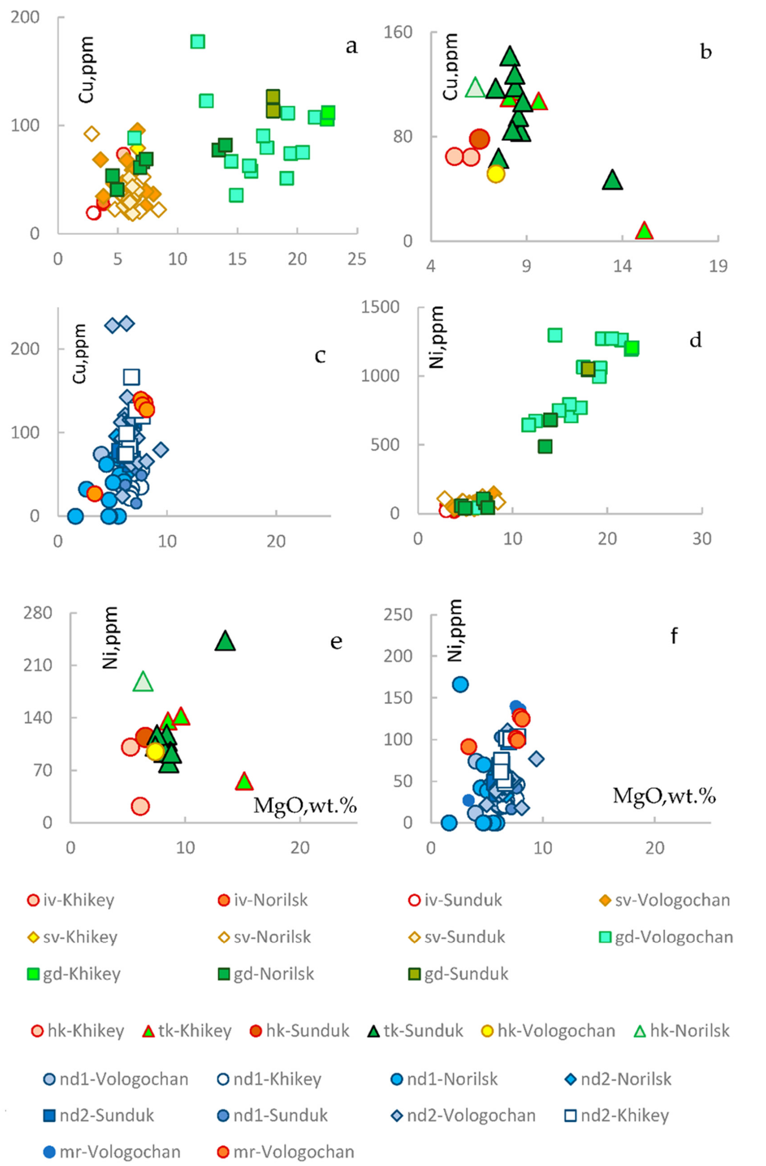

Figure 18. Diagrams MgO vs. Cu (**a**–**c**) and Ni (**d**–**f**) for volcanic rocks ((**a**,**c**)—Ivakinsky, Syverminsky, Gudchikhinsky Formations; (**b**,**e**)—Tuklonsky Formation; (**c**,**d**)—Nadezhdinsky, Morongovsky Formations).

Cobalt demonstrates the best subdivision of the rocks. Its contents vary considerably in the rocks of the different Formations. The maximum concentrations (150–200 ppm) were established in the Syverminsky Formation, distributed within the Vologochan syncline (Figure 19a). The remaining low-Mg rocks (Ivakinsky, Syverminsky, and Gudichikhinsky Formations) contain low Co concentrations (30–50 ppm). The Tuklonsky Formation is depleted in cobalt, even in comparison with the Ivakinsky and Syverminsky rocks (Figure 19b). The basalts of the Nadezhdinsky Formation are also ranked in the Co content; the lowest concentrations are characteristic of its lower and middle subformations, especially in Mount Sunduk. Perhaps, the latter does not reflect reality because the division into subformations in the Mount Sunduk section is not very clear due to the similarity of the Nadezhdinsky rocks in texture and structure. Although Zn concentrations (Figure 19d–f) vary in volcanic rocks, especially in the Nadezhdinsky Formation, they do not indicate different formations.

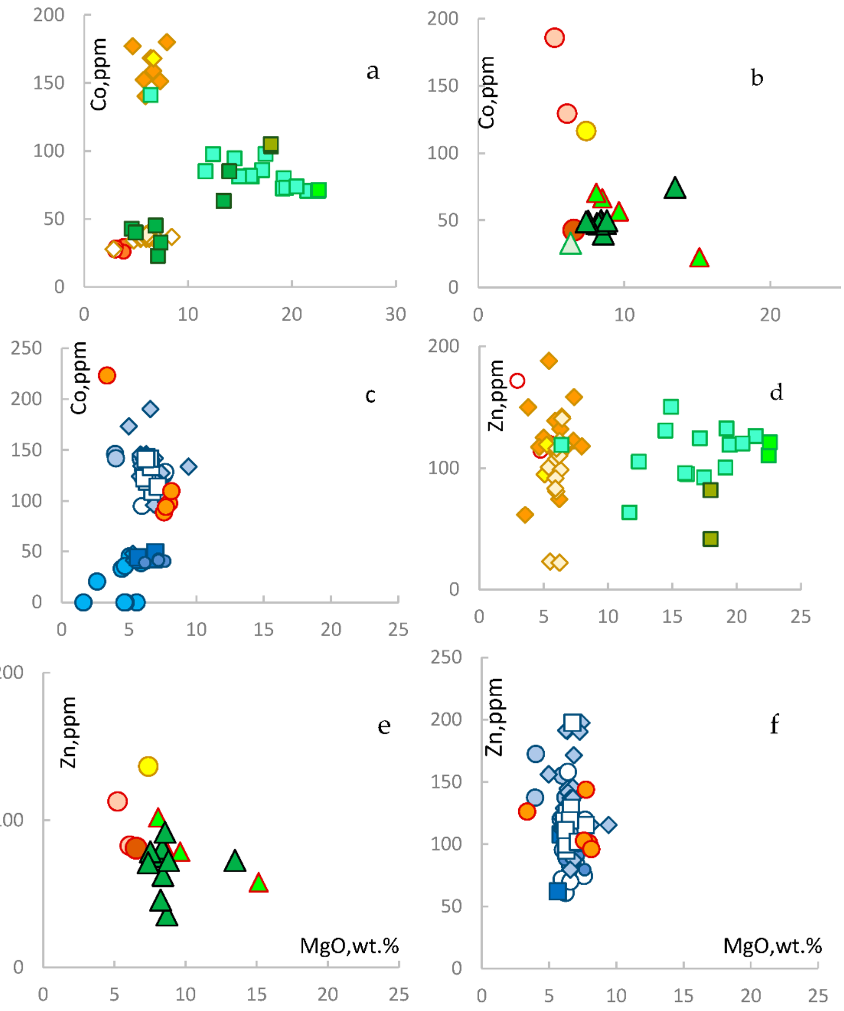

Figure 19. Diagrams MgO vs. Co (**a**–**c**) and Zn (**d**–**f**) for volcanic rocks. Captions in Figure 18.

The metal contents in the studied sills and barren rocks of the South Pyasinsky intrusion (only rocks with a sulfur content <0.2 wt.% were selected) are very similar. First, this concerns the Cu and Co contents in the sill from the Vologochan syncline (Sill-Volgochan in Figure 20a,d). The nickel concentrations in the South Pyasinsky intrusion are higher in olivine gabbro–dolerites due to the Ni entry into the olivine lattice. Increased values of Zn are noted in the sills compared with the ore-bearing intrusion, especially in the massif from the Khikey River valley. Thus, the ore-bearing intrusions of the Norilsk complex are not characterized by abnormal contents of ore elements; the compositions of the initial melts of lavas and intrusions are very similar.

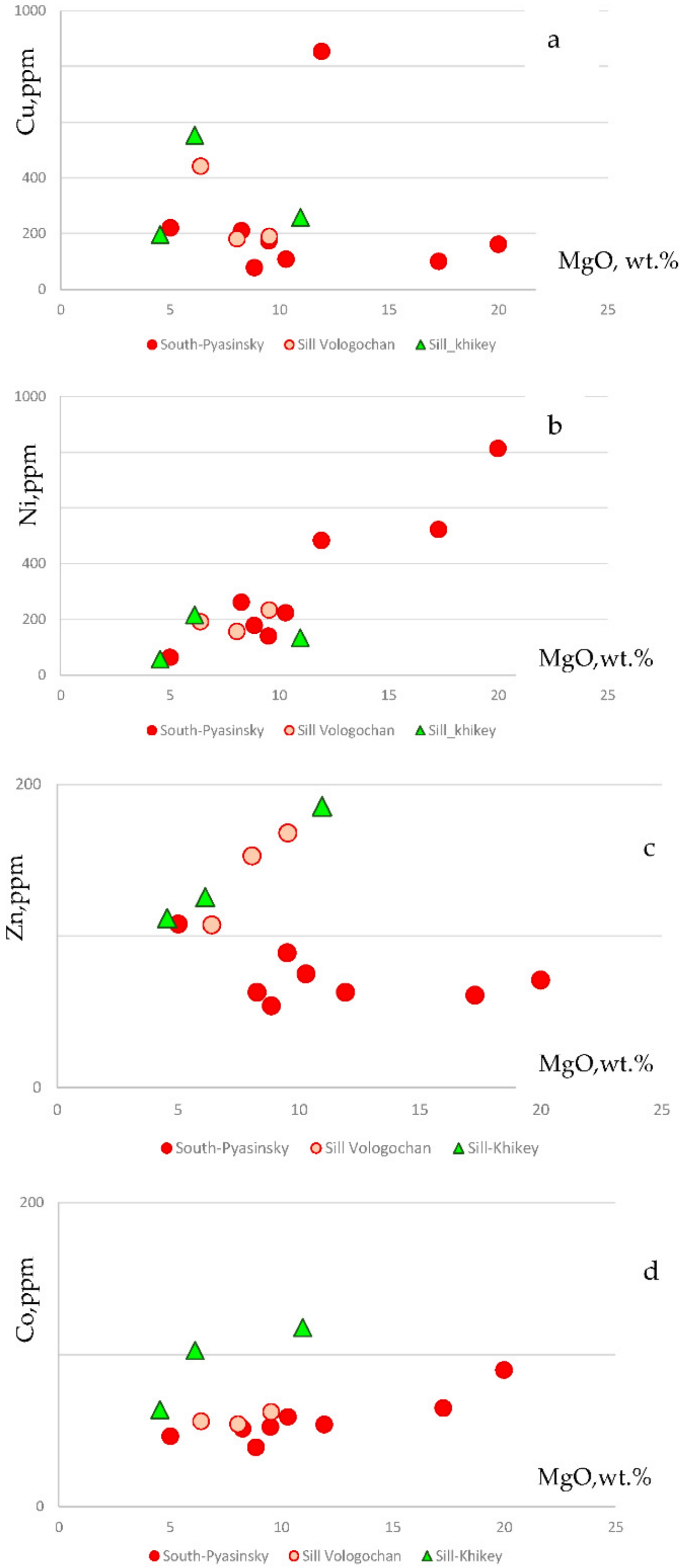

Figure 20. Diagrams MgO vs. Cu (**a**), Ni (**b**), Zn (**c**), and Co (**d**) for intrusive rocks. Captions in Figure 16.

5. Discussion

The origin of volcanic rocks is important for understanding the relationships between the ore-bearing intrusions and basalts. Initially, it was suggested that all magmatic rocks of the province were a result of a single magma fractionation [1,27]. Later, the diversity of rocks was interpreted as the products of different magmas formed from different sources, where the processes of the magmas' mixing and assimilating the host rocks played an important role. As noted above, based on the geochemical data, the products of the OIB (Ivakinsky-Gudchikhinsky Formations), transitional series (Khakanchansky-lower Morongovsky Formations), and the WPB (middle Morongovsky-Samoyedsky Formations) were distinguished [29]. This division was made on the basis of single sections and did not consider the geological structure of volcanic rocks, i.e., the morphology of flows and their distribution.

For the first time, we studied the effusive rocks around the area (three sections are characterized in this article and one section in [41]). The rock structure and texture cannot be used for the comparison of the volcanic sections located at a great distance apart because they often fluctuate within one flow from bottom to top and along the strike. Many mineralogical data for volcanic rocks are given in [45] but they do not allow to identify systematic differences in Formations due to their chaotic distribution within the area as well. Our data demonstrate strong variations in the structure and composition of the lower and middle Formations.

Firstly, it is found there are variations in the Formations' thicknesses. The Ivakinsky Formation is absent in some areas of the Vologochan syncline, which evidences an uneven surface at the end of the Permian age. It, and the Syverminsky Formation, pinch out to the east of the Norilsk region in the Putorana Plateau. The Gudchikhinsky and Tuklonsky Formations dramatically change their thickness from 210–240 m to 0 m in different directions: the first one to the east and the second one to the west (Figure 7). The Nadezhdinsky Formation is characterized by fewer differences in its thickness, which reduces to the east. These features of the volcanic sequences reflect the structure of the NW Siberian Platform in the early Triassic time, when a depression (a part of the Yenisey-Khatanga trough?) occurred here and controlled the magma intrusions. Thus, the sources of these Formations were located in the west, within the Yenisey-Khatanga trough, while the source of the Tuklonsky magma was in the Tunguska syneclise.

Secondly, the formation compositions change in the same direction as their thicknesses, i.e., from the west to east. First of all, this is typical of the Gudchikhinsky, Nadezhdinsky, and Lower Morongovsky Formations. For example, this is clearly visible for the rocks of the Gudchikhinsky Formation from the picrites, which occur in all the sections. These rocks have the most primitive composition in the eastern part of the district, in the Mount Sunduk section (CY-19/1) (Figure 21a). They have undergone crustal contamination in the west (Vologochan syncline, samples OV-36/692.5, OV-36/701.2), i.e., they have weakly manifested Ta-Nb negative and Pb positive anomalies, and higher concentrations of uranium, as well (Figure 21a), as demonstrated earlier [40]. For the Nadezhdinsky and Morongovsky Formations, the enrichment in the trace elements also occurs in the west, where the Pb and U anomalies increase. Probably, these regularities can be explained by different conditions of the magma penetration: within the eastern rigid block, represented by the Khantajsko–Rybninsky swell, the magmas quickly reached the surface while, in the west, in a paleo depression they could assimilate a few sedimentary rocks (Figure 22). All the rocks were folded later (see Cross-section I-I in Figure 2).

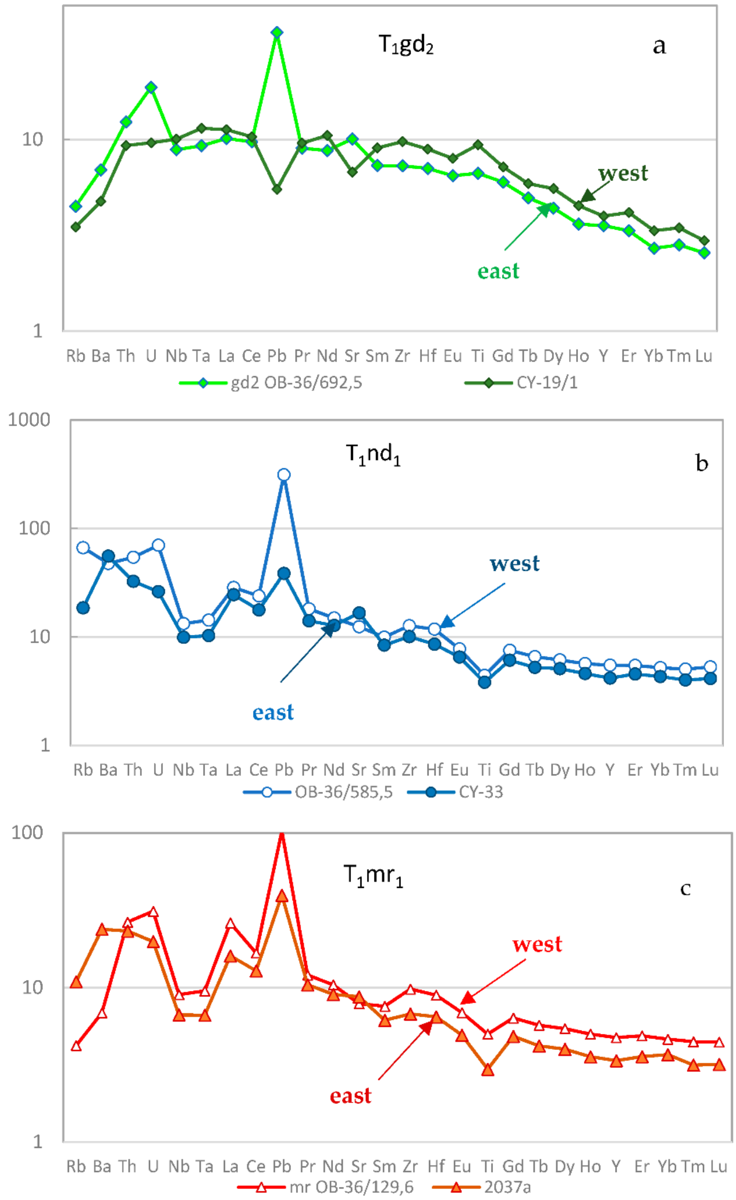

Figure 21. Patterns for rocks from the west and east parts of the Norilsk area; Gudchikinsky picrits (**a**), Nadezhadinsky (**b**) and Morongovsky (**c**) basalts.

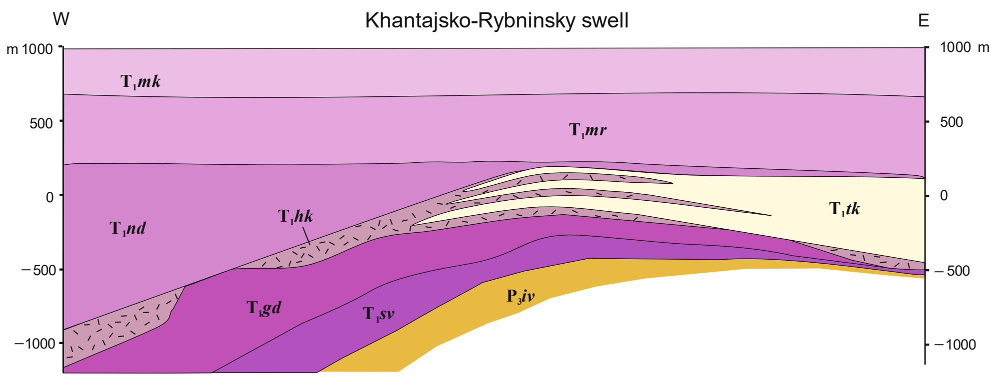

Figure 22. Reconstruction of tuff–lavas structure in the Norilsk area for Early Triassic time.

Regarding the classification of the volcanic rocks into OIB, transitional and WPB, we can conclude that it is not very successful. The compositions of the three lower Formations indicate that only the Gudchikhinsky Formation can be attributed to the OIB (Figure 9), while the two others have crustal signatures (isotopic characteristics and trace element patterns). They are similar only in the Gd/Yb ratio, indicating the presence of garnet in the source. The Formations enriched in the light lithophile elements were classified as a transitional series, including the Nadezhdinsky and Morongovsky Formations. The composition of the last formation changes significantly from east to west, where it is close to the Mokulaevsky Formation [6]. Taking into account that it is widespread around the platform, it should be associated with a typical WPB (traps), with local contamination in the west.

Therefore, we believe that Al'mukhamedov et al. [32] classified the volcanic rocks into genetic types more correctly and subdivided them into the rift and platform formations. We see that the Yenisey–Khatanga trough controls the formation distributions determined as rift formations. Although these authors believe that they overlapped with the platform in time, we have shown that they could have been formed synchronously [43].

The setting of the Norilsk deposits within the Siberian magmatic province requires the determination of the genetic links between the lavas and the ore-bearing intrusions. For the first time, Godlevsky [1] identified the four cycles in the magmatic evolution on the basis of studying the structure and composition of the tufa–lava sequence. One cycle includes (from the beginning to the end) tuffs, lavas, and intrusions. The latter could be synchronous with the formation of the volcanic rocks or follow them. According to this scheme, the intrusions of the Norilsk complex were formed from an independent magma at the last stage of the second cycle, after the Gudchikhinsky Formation. Later, Dyuzhikov [5,46] suggested a common source for the ore-bearing intrusions and the Gudchikhinsky rocks by taking into account the occurrence of high-Mg varieties in them (picritic gabbro-dolerites and picrites, respectively). However, new analytical data (trace elements distributions, isotope data) have shown significant differences between these rocks [30,40].

The primary direct connections between the intrusions and lavas were first suggested by Ivanov in 1967 and published in 1971 [47]. This idea was revived after the publication of Radko [12], who suggested that an ore-bearing intrusion is a horizontal part of a channel that supplied the Mokulaevsky magma to the surface. Within the framework of this model, Naldrett linked the formation of ores with the sulfide settling from the early portions of the Nadezhdinsky magma, on the basis of the depletion of the Nadezhdinsky rocks in the non-ferrous and platinum-group metals [13]. Likhachev criticized this idea [5] because the Nadezhdinsky magma was unsaturated in sulfur and, thus, it could not produce any sulfides. According to Latypov [48], effusive rocks are not in equilibrium with olivine and, therefore, cannot be linked with ore-bearing intrusions enriched in olivine. However, the Nadezhdinsky formation contains olivine basalts and picrites [49]. Therefore, such calculations [48] do not prove the absence of this connection. In addition, the composition of the Nadezhdinsky rocks differs significantly from the ore-bearing intrusions [31,37].

The ore-bearing South Maslovsky massif shows the absence of a direct link between these rocks because it cuts the lower subformation of the Nadezhdinsky Formation [50]. Krivolutskaya stated this fact in a personal communication with Naldrett in 2008 [51], which led to the appearance of a two-stage model of the formation of the Norilsk deposits, i.e., the sulfide settled from the Nadezhdinsky magma at depth and then were transported by the Morongovsky magma to the shallow zone of the crust [14]. Thus, again, this model does not consider the undersaturation of the Nadezhdinsky magma in sulfur. Another important argument against an open-system model is the completely different sulfur isotope composition of the sulfides from intrusive and effusive rocks, as shown in Figure 23.

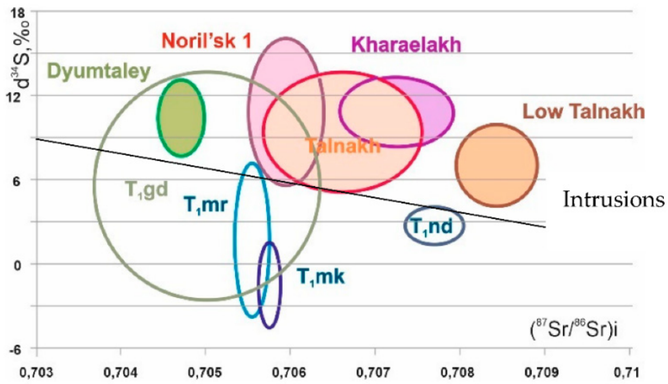

Figure 23. Diagram $(^{87}Sr/^{86}Sr)_i$ vs. $\delta^{34}S$ for intrusions and basalts in the Norilsk area. Data from [52–56].

The PGE-Cu-Ni deposits are concentrated in a narrow zone within the Norilsk–Igarka paleorift structure, to which the rift formations are confined (Figure 24). Such spatial distribution may indicate their genetic links. Although, in general, the concentrations of metals in volcanites do not differ from those in the barren rocks of the Norilsk intrusive complex, the copper and nickel contents increase in the basalts and picrites of the Gudchikhinsky Formation. However, the most important aspect is that the Gudchikhinsky Formation is enriched in heavy sulfur [53] (Figure 23), although the article's authors did not note this fact. This indicates a possible link between the Gudchikhinsky sulfides and the sulfides from the ore-bearing intrusions, despite the difference in the rock compositions. According to our assumption, the sulfides could have formed in the mantle conditions corresponding to the conditions of the Gudchikhinsky magma formation [40] and been transported to the lower crust. Their further mobilization and transport took place from the lower crust to its upper horizons by the trap magmas (Figure 25).

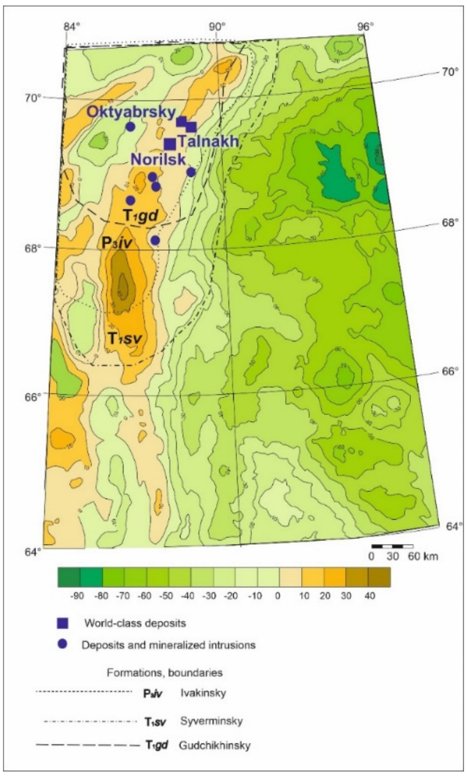

Figure 24. PGE-Cu-Ni deposits and boundaries of rift formations on the map of the isoanomals of the gravitational field (in conventional units) in the Buge reduction (c = 2.67 g/cm^3) at altitude 1.6 km for the NW Siberian platform [57].

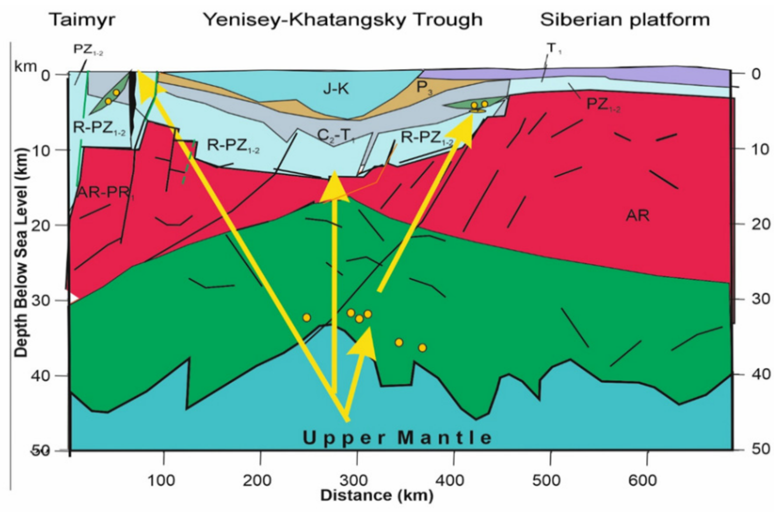

Figure 25. Schema of deposits' formation in the NW Siberian Platform.

6. Conclusions

1. For the first time, the structural and geochemical variations along the strike of the Ivakinsky, Syverminsky, Gudchikhinsky, Khakanchansky, Tuklonsky, Nadezhdinsky, and Morongovsky Formations are demonstrated on the basis of the volcanic sections in the Vologochan syncline (borehole OB-36), Khikey River valley, and Mount Sunduk. The thickness of the Formations, excepting the Tuklonsky and Morongovsky, reduce from the Yenisey–Khatanga trough to the Tunguska syneclise, up to their disappearing synchronously with the change in composition. This location in the Norilsk–Igarka paleorift and the compositional variabilities in the rift rocks differ them from the platform basalts.
2. The coinciding of the location and metal contents in the volcanic and ore-bearing intrusive rocks propose their genetic link. The Gudchikhinsky magma could be a source of the sulfide in the deposits, due to its elevated Cu and Ni concentrations and heavy $\delta^{34}S$.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/min12101203/s1, Figure S1: Textural and structural characteristics of effusive rocks (microphotographs); Table S1: Composition of rock-forming minerals in volcanic rocks of different formations, wt.%; Table S2: Rock compositions in borehole OB-36; Table S3: Volcanic rock compositions, r. Khikey; Table S4: Volcanic rock compositions in Sunduk Mount.

Author Contributions: Conceptualization and field trip, N.K.; geological mapping in field trips and building of cross-sections, V.M.; geochemical and mineralogical study of the rocks by EPMA and LA-ICP-MS, D.K.; documentation and sampling of the borehole, B.G.; samples preparation, N.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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